

A cross-country network analysis of disease infodemics: Looking through the lens of the COVID-19 pandemic

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ABSTRACT

Infodemics surrounding pandemics and epidemics have persisted for centuries and continue to impede efforts to promote high vaccination coverage. We explored the complex interplay between COVID-19 vaccination attitudes and COVID-19-related infodemics across Germany, Ghana, India, and New Zealand using the novel network analysis. We conducted an online cross-sectional survey and recruited 1822 participants from the general populations of India ($n = 411$), New Zealand ($n = 413$), Ghana ($n = 523$), and Germany ($n = 413$) to complete COVID-19 infodemic measures and demographics questions. Predictors of less favourable COVID-19 vaccination attitudes included the apocalypse-related infodemic in India, compared to all countries, as well as the not harmful belief of COVID-19 in New Zealand, compared to India and Germany, and in Ghana compared to India. COVID-19 origin-related infodemics were found to positively impact COVID-19 vaccination attitudes in Ghana and New Zealand only. The most influential infodemics in each of the countries studied-Ghana, New Zealand, Germany, and India-were the beliefs in bioweapons, 5G technology, apocalypse, and bat consumption, respectively. Across all countries, there were consistent strong positive connections between the infodemics. Our results suggest that country-specific infodemics significantly impact COVID-19 vaccination attitudes, with variations observed between nations. While the infodemics can reinforce each other and complicate public health efforts during pandemics, understanding the interactions between the central infodemic in each country and others can aid in developing more effective strategies to counter their influences. This highlights the importance of targeted public health interventions that address the unique dynamics of local infodemics during pandemics, epidemics, and Pathogen X outbreaks.

1. Introduction

Infodemics surrounding pandemics and epidemics have persisted for centuries. Public health campaigns to combat some of the world's most impactful pandemics and epidemics such as the Ebola, HIV/AIDS, and COVID-19 are ongoing [1]. The World Health Organization (WHO) conceptualizes infodemics as dissemination of false or misleading information in either digital or physical settings during disease outbreaks [2]. Infodemics include a range of beliefs, such as conspiracy theories, misinformation, and disinformation. However, our study has not

specifically distinguished between these terms. Instead, we have collectively referred to them as forms of informational distortions known as infodemics and explored their impact on vaccination attitudes. The infodemics witnessed during the COVID-19 pandemic, as well as previous outbreaks like Ebola and HIV/AIDS, are likely recurrent patterns (also experienced in previous pandemics). These patterns encompass widespread tendencies to initially downplay the severity of deadly diseases and persistently harbour scepticism and mistrust towards governments, scientific institutions, and pharmaceutical companies [3,4]. Therefore, the present study is valuable not only for the current

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pandemic, but also for future pandemics, particularly considering the emergence of Pathogen X [5]. Vaccine hesitancy due to infodemics poses a significant challenge to Pathogen X eradication or suppression.

Infodemic beliefs tend to stem from a multifaceted blend of historical, cultural, emerging anxieties, socio-political, and psychological factors, as well as influences from mythology [6]. As a result, the impact of infodemics on efforts to achieve high vaccination coverage does not exhibit universal and consistent trends. Examples of these include beliefs such as considering COVID-19 as both a biological weapon and a myth, contributed to COVID-19 vaccination hesitancy attitudes [3]. However, contrary findings have been reported by other studies, indicating a positive correlation between these beliefs and the willingness to accept COVID-19 vaccination [3]. Furthermore, researchers have reported that beliefs linking the COVID-19 pandemic to deliberate creation by pharmaceutical companies for profit, the installation of 5G mobile networks, and the belief that the COVID-19 is not harmful, were associated with lower willingness to get vaccinated against COVID-19 [7,8]. Religious-related infodemics, such as the belief that COVID-19 is humanity's destiny and a sign of the end-times (apocalypse), were also associated with more favorable attitudes towards COVID-19 vaccination [9]. These diverse links clearly demonstrate that several factors may interact with infodemics to influence health outcomes.

Consequently, the literature has highlighted the mediating roles of various sociocultural and psychological factors in the relation between infodemics and vaccination. Specifically, elevated levels of negative vaccine confidence, complacency, limited vaccine knowledge, and medical mistrust have been identified as key mediators of the link between COVID-19 vaccination hesitancy and exposure to infodemics [10,11]. Certain personality traits increase susceptibility to infodemic beliefs, which subsequently influence health behaviors. Individuals exhibiting narcissistic tendencies, paranormal beliefs, and low perceived self-control are particularly vulnerable. These traits predispose individuals to accept and propagate misinformation and indirectly influence health behaviors like vaccination. For example, narcissism may lead to distrust in expert recommendations, while low self-control can impair critical evaluation of information, ultimately shaping attitudes and behaviors towards vaccination [12]. Cognitive biases, including the conjunction fallacy, proportionality bias, and agency detection bias, contribute to the development of false beliefs about diseases, which in turn shape health behaviors and influence decisions such as vaccination [13]. Furthermore, Blackburn et al. [14] found that a lack of trust in government and science mediated the link between conspiracy beliefs and COVID-19 vaccination hesitancy.

The inconsistent results observed in the relation between infodemics and COVID-19 vaccination behavioral intentions indicate that their links are not well understood in the extant literature. We also observed that the influence of infodemics on health outcomes could be mediated by a range of biopsychosocial factors. Such inconsistent patterns of the interconnectedness and the complex role of infodemics in the health literature highlight the multidimensional nature of factors that influence health outcomes and well-being, including vaccination [15]. This complexity further emphasises the importance of using appropriate statistical methodologies to examine the intricate interactions among health-related variables, including infodemics and COVID-19 vaccination attitudes [16]. However, the present COVID-19 related literature, including health research, has often adopted a rigid and arbitrary approach, treating variables as simple cause-and-effect relations in studies, for example, using regression analysis [17]. While such statistical approaches provide valuable insights for health interventions, they could result in a limited understanding of the reciprocal influences of health-related factors, including infodemics and COVID-19 vaccination attitudes, as proposed by the current biopsychosocial approach to health and well-being [18,19,20].

Recently, the field of health psychology is increasingly employing the novel 'network analysis' technique to explore the complex connections among various factors that influence health and well-being

[20,16]. Network analysis, a statistical technique rooted in the biopsychosocial model of health [21], is particularly well-suited for health psychology, which examines the influence and interactions of biological, social, and psychological variables on health outcomes. The biopsychosocial model views health outcomes as the result of the embodiment and interaction of biological, psychological, and social factors, rather than focusing solely on a single factor (Engel, 1977). Similarly, network analysis proposes that outcomes are conceptualised as systems of causally interrelated variables, modelling the complex associations between predictors and outcomes [22,20]. This approach offers a robust method for uncovering the complex links between variables and validating theoretical connections [23]. It further quantifies the significance of each variable within the model, identifying the most influential variables for targeted interventions [22,24]. These parameters help enhance our understanding of the dynamics of health-related factors [15,20].

Another limitation that has been identified in the literature is the narrow scope of research on this topic, which has predominantly centered on specific population groups. In essence, a lack of cross-cultural comparative studies has been found, resulting in a segmented understanding of the links between infodemics and attitudes towards COVID-19 vaccination. Meanwhile, research has also indicated that cultures influence beliefs, including infodemics [25], and sociodemographic groups are impacted differently by infodemics [26]. We have found that the majority of previous studies were mostly descriptive (i.e., reporting prevalence rates of infodemics), and often failed to evaluate the impact of infodemics on vaccination attitudes. Our study aimed to explore the complex interrelatedness between attitudes towards COVID-19 vaccination and COVID-19-related infodemics across four countries spanning four continents, encompassing Germany, Ghana, India, and New Zealand using the novel network analysis.

2. Methods

2.1. Participants

Our study included 1822 participants from the general populations of Ghana ($n = 523$), Germany ($n = 475$), India ($n = 411$), and New Zealand ($n = 413$). The ages of participants ranged from 18 to 80 years in India ($M_{age} = 26.14$; $SD = 8.57$), 18 to 89 years in New Zealand ($M_{age} = 46.35$; $SD = 18.07$), 18 to 63 years in Ghana ($M_{age} = 29.48$; $SD = 5.69$), and 18 to 87 years in Germany ($M_{age} = 44.09$; $SD = 5.57$). In New Zealand, the ethnic composition was as follows: 275 participants (67 %) identified as Europeans, 36 (9.2 %) as Asians, and 68 (17 %) as other ethnicities. In the German sample, the majority identified as Germans ($n = 396$; 83 %), with the remaining participants ($n = 79$; 17 %) identifying as other nationalities. All participants from India and Ghana identified themselves as Indian and Ghanaian, respectively. Sex distribution in Ghana was 338 males (65 %) and 185 females (35 %). In Germany, there were 223 males (48 %) and 244 females (52 %). Among the Indian participants, 130 were males (30 %) and 281 were females (68 %). In New Zealand, 179 participants were males (43 %) and 234 were females (57 %).

2.1.1. Power analysis

Monte Carlo sample size simulation-based methods have recommended that a minimum sample size ranging from 250 to 350 participants is required to achieve valid and reliable parameters, such as sensitivity, specificity, and weight correlations for psychological network analysis consisting of 20 nodes or fewer [27].

2.2. Procedure

The authors received ethical approval from their institution's Human Research Ethics Committee for the present study. Data from Ghana and India were gathered using [SelectSurvey.net](https://www.selectsurvey.net) software utilizing platforms

such as WhatsApp, Instagram, twitter, Email, and Facebook. We employed convenience sampling via snowballing techniques. Participants from India and Ghana did not receive any form of compensation for taking part in this study. This was because researchers in India and Ghana utilised their extensive social networks to gather data in these two countries. In contrast, researchers contracted the services of Qualtrics data collection company to collect data from New Zealand and Germany, and participants were compensated by this company (e.g., NZ \$5 or a possibility to participate in a draw). Participation in the study was voluntary, and individuals aged 18 and above were eligible. The questionnaire encompassed demographic aspects such as age, sex, and ethnicity, along with the main infodemic questions. On average, participants spent 15 mins completing the questionnaire. The data for the current study were gathered in mid-2022 and form part of a larger dataset examining the factors linked to COVID-19 vaccination attitudes, applying varied conceptual and methodological approaches.

2.3. Measures

2.3.1. COVID-19 vaccination attitudes

Attitudes towards COVID-19 vaccination was measured employing the 9-item version of the Motors of COVID-19 Vaccination Acceptance Scale (MoVac-COVID19S) [28]. This scale assesses individuals' favorable and unfavorable attitudes regarding accepting the COVID-19 vaccine. This scale is available in both English and German languages [29]. Participants rated items on a 7-point Likert scale ranging from 1 = "strongly agree" to 7 = "strongly disagree". An example item is: "vaccination is a very effective way to protect me against COVID-19". We used the Rasch methodology-based algorithm to transform the traditional ordinal scores of this scale into interval-level scores, increasing the precision of the scores. The interval scores demonstrated excellent reliability using the Person Separation Index (PSI = 0.90).

2.3.2. Infodemics measures

The current study assessed ten COVID-19 infodemics commonly examined in previous literature [3,30]. Each adopted infodemic was evaluated using a single item scored on a five-point Likert scale ranging from 1 = "strongly disagree" to 5 = "strongly agree". Items included: "I believe that the COVID-19 pandemic is a punishment from God as a result of humanity's sinful acts" [31], "I believe that the presence of COVID-19 is one of the signs of the end-time (apocalypse) preached by various religions [31], "I believe that COVID-19 crisis was deliberately created in order to keep people at home while 5G engineers install the technology everywhere [3]", "I believe that the COVID-19 was created in a Chinese laboratory [32]", "I believe that the Coronavirus was designed as a bioweapon (to reduce the world population; [3])", "I believe that COVID-19 originated as a result of Chinese eating bat meat and the virus passed from bats to humans [33]", "I believe that COVID-19 vaccination will change my genetic make-up [34]", "I believe that COVID-19 is not harmful and, therefore COVID-19 vaccination is not necessary [3,29,35]", and "I believe that COVID-19 has been deliberately spread by the elite and the rich families of the world [32]".

2.4. Statistical analyses

2.4.1. Data preparation

The data underwent initial preparation in IBM Statistical Package for the Social Sciences (SPSS; version 28). A test for Missing Completely at Random (MCAR) based on Little's [36] method was conducted, yielding a non-significant result ($p = 0.071$). This implies that the missing data were random, suggesting that there were no systematic patterns in the missing data that could bias the results. We addressed the few missing data points using the Expectation Maximization (EM) algorithm data imputation technique [37]. The descriptive statistics were analysed using the SPSS software. For the network analysis, RStudio software (version 4.3.3; [38]) was utilised.

2.4.2. Main analyses

We first conducted an exploratory network analysis to examine the interrelation between the 10 identified infodemics and attitudes towards COVID-19 vaccination. To do this, we employed the Bayesian Gaussian Graphical Models (BGGM) package in R. Supplementary Text S1 provides explanation for the BGGM. This package was used as different types of variables, including continuous and non-continuous can be used in the model [39]. Each of the variables (i.e., infodemics and COVID-19 vaccination attitudes) in the network were classified as nodes. The BGGM package analyses how these nodes (variables) are connected to each other. Unlike the traditional Pearson's correlation, which does not account for non-linear relations, the BGGM considers the simultaneous effects of all variables on each other. In simple terms, we examined how each infodemic and attitude towards COVID-19 vaccination impact each other when accounting for all the other factors (i.e., computed as posterior means; [16]).

Instead of using the traditional *p-values* to assess significance, a more robust method called credible intervals (CI) was employed to create a partial correlation matrix. This method only retains associations within the 95 % CI that do not include zero [18,19]. If a 95 % CI does not include zero, it indicates an automatic and strict significance of the *p-value*. The BGGMs were computed for each country using the 'qgraph' in R library, which utilises the Fruchterman-Reingold algorithm to visualize networks [40]. The network layout was averaged across the models to improve comparison by countries [41]. The absence of edges between nodes indicates that the CIs of the edge weights include zero, reflecting insufficient confidence in an association. In psychological network analysis, the distance between two nodes is called an "edge," and the assigned value is the "weight of the edge." The statistical coefficient between two nodes is referred to as "weight edge," indicating the type of interaction (positive or negative) between the nodes. The absolute value of the weight edge indicates the strength of the effect, typically assigned a numerical value ranging from -1 to +1 [20].

2.4.3. Estimating differences

We calculated the mean difference for each node-to-node association in the four countries to determine whether there were statistically significant differences in the associations between the four countries [42], comparing each country to the other. We then established 95 % CIs for these differences using 5000 posterior estimates. Differences were deemed statistically meaningful if the 95 % CIs of the mean differences did not include zero [18,19].

2.4.4. Predictability estimate

In the current analyses, researchers deliberately focused on predictability rather than the traditional centrality measures, as it offers several key advantages specific to BGGM. Predictability quantifies how well a variable can be predicted by all its neighbouring nodes in the network, conceptually similar to R-squared in regression analysis [18,19,24]. This makes it particularly interpretable and meaningful in the context of psychological networks, where we are often interested in understanding how well we can predict one psychological construct from related constructs. Unlike the traditional centrality measures that focus solely on structural positions within the network, predictability provides direct insights into the functional relations between variables, making it especially valuable for intervention planning [24]. Predictability was calculated using the 'predictability' function in R, following established procedures [24], providing clear insights into which variables might be most promising for intervention targets.

2.4.5. Stability estimates

We ensured the robustness and stability of our predictability and other estimates through several methodological choices. Our analyses employed 5000 Markov Chain Monte Carlo (MCMC) iterations with a specified seed of 1, ensuring reproducible results [43]. We used conservative priors (standard deviation of 0.25) to enhance model stability

and reduce the impact of extreme estimates. An example of the complete estimation syntax is provided in Supplementary Table S1.

3. Results

3.1. Common relations between COVID-19 vaccination attitudes and infodemics

Results from Fig. 1 (illustrates the network models of unique associations between the infodemics and COVID-19 vaccination attitudes for each country) showed that in both Ghana (*weight edge* = -0.36) and New Zealand (*weight edge* = -0.41), the belief that COVID-19 is not harmful was strongly and independently *negatively* linked to COVID-19 vaccination attitudes (Fig. 1: Supplementary Table S1). While this link was found to be within the 95 % CI in New Zealand compared to the Indian and German sample, it was within this CI in Ghana only when compared to the Indian sample (Figs. 2, 3, and 4 show estimated differences between countries for each node-to-node link). The belief that the COVID-19 pandemic originated because of Chinese eating bat meat was independently and *positively* related to COVID-19 vaccination attitudes in these countries as well: Ghana (*weight edge* = 0.17); New Zealand (*weight edge* = 0.14; Fig. 1: Supplementary Table S1). This relation fell within the 95 % CI in Ghana when compared to the German and Indian samples, and in New Zealand compared to the Indian sample (Figs. 2, 3, and 4). Further, the belief that COVID-19 vaccine can cause changes to one's genes linked uniquely and *negatively* to attitudes towards COVID-19 vaccination in both Ghana (*weight edge* = -0.13) and New Zealand (*weight edge* = -0.17; Fig. 1: Supplementary Table S1). Notably, this link was not within the 95 % CI for these countries, in contrast to Germany and India. (Figs. 2, 3, and 4). However, among the Indian (*weight edge* = 0.18) and New Zealand (*weight edge* = 0.15) participants, the belief that

the COVID-19 pandemic is a punishment from God because of humanity's sinful acts uniquely and *positively* related to COVID-19 vaccination attitudes (Fig. 1: Supplementary Table S1). Notwithstanding, this link fell within the 95 % CI in both countries when compared to the Ghanaian sample (Figs. 2, 3, and 4).

Additionally, across all the countries, we observed strong *positive* links between the belief that the COVID-19 pandemic is a bioweapon intended to reduce the world's population, the belief that COVID-19 was created in a Chinese laboratory (German: *weight edge* = 0.16; Ghana: *weight edge* = 0.64; India: *weight edge* = 0.44; New Zealand *weight edge* = 0.57; Supplementary Table S1), and the belief that COVID-19 was deliberately spread by elites in the world (German: *weight edge* = 0.49; Ghana: *weight edge* = 0.22; India: *weight edge* = 0.17; New Zealand *weight edge* = 0.42; Supplementary Table S1). We also noted strong *positive* relations between the belief that COVID-19 is one of the signs of the end-time preached by various religions and the belief that the COVID-19 pandemic is a punishment from God due to humanity's sinful acts (German: *weight edge* = 0.77; Ghana: *weight edge* = 0.63; India: *weight edge* = 0.62; New Zealand *weight edge* = 0.57; Supplementary Table S1). Furthermore, we found strong *positive* link between the belief that the COVID-19 vaccine can cause infertility and the belief that COVID-19 vaccination can alter one's genetic makeup (German: *weight edge* = 0.42; Ghana: *weight edge* = 0.32; India: *weight edge* = 0.34; New Zealand *weight edge* = 0.32; Fig. 1: Supplementary Table S1).

3.2. Unique relations between COVID-19 vaccination attitudes and infodemics

In India only, the belief that COVID-19 pandemic is one of the signs of end-time preached by various religions related *negatively* and independently to attitudes towards COVID-19 vaccination (*weight edge* =

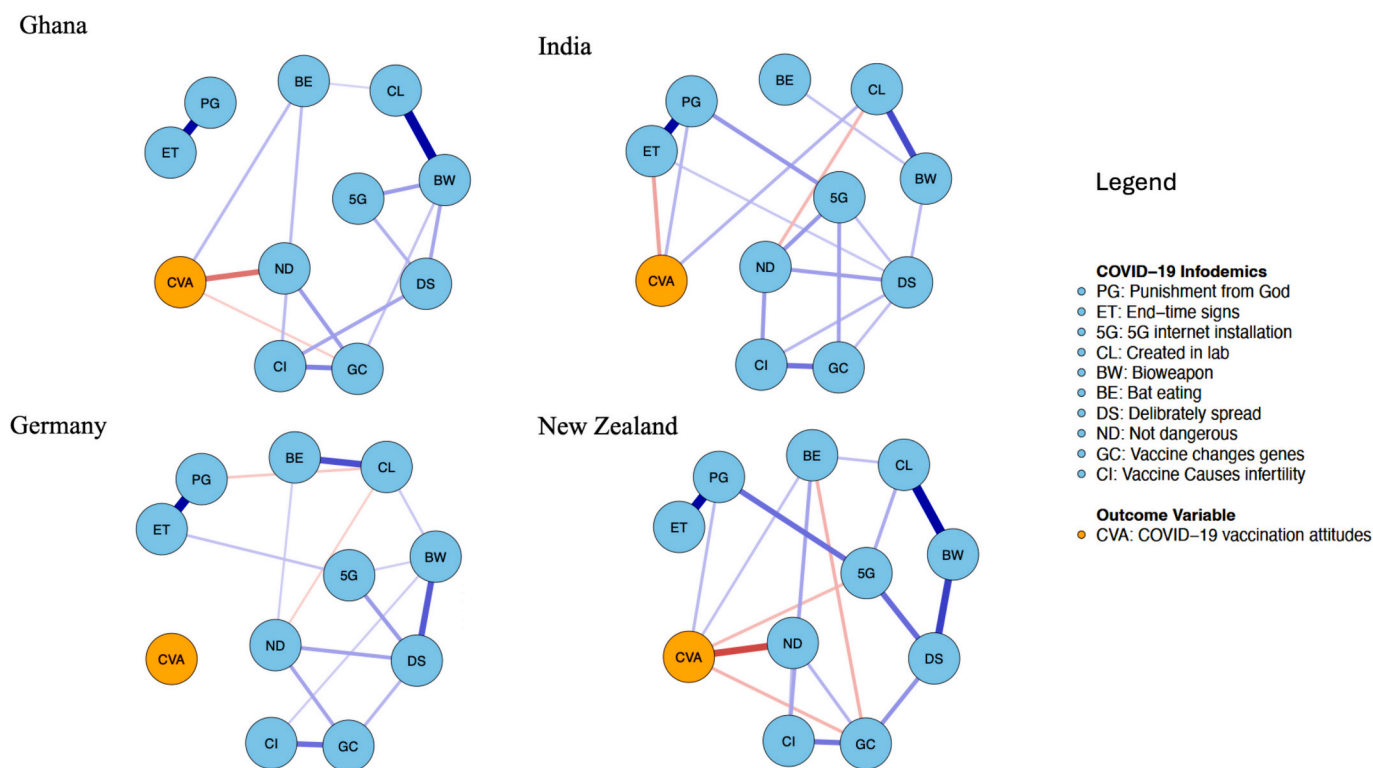


Fig. 1. Bayesian gaussian graphical models (BGGMs) networks of COVID-19 related infodemics linked COVID-19 vaccination attitudes. Only associations which 95 % credible interval did not include zero were printed. Note: PG = God's punishment belief, ET = end times belief, 5G = 5G internet technology belief, CL = COVID-19 created in lab belief, BW = bioweapon belief, BE = bat eating belief, DS = deliberately spread belief, ND=COVID-19 not harmful belief, GC = genetic change belief, CI=COVID-19 vaccine cause infertility belief, CVA = COVID-19 vaccination attitudes. The blue edges reflect significant positive relations between variables while the red edges signify negative relations. The strength of associations is shown by the thickness and depth of the colour of edges; a darker edge suggests a stronger association and vice versa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

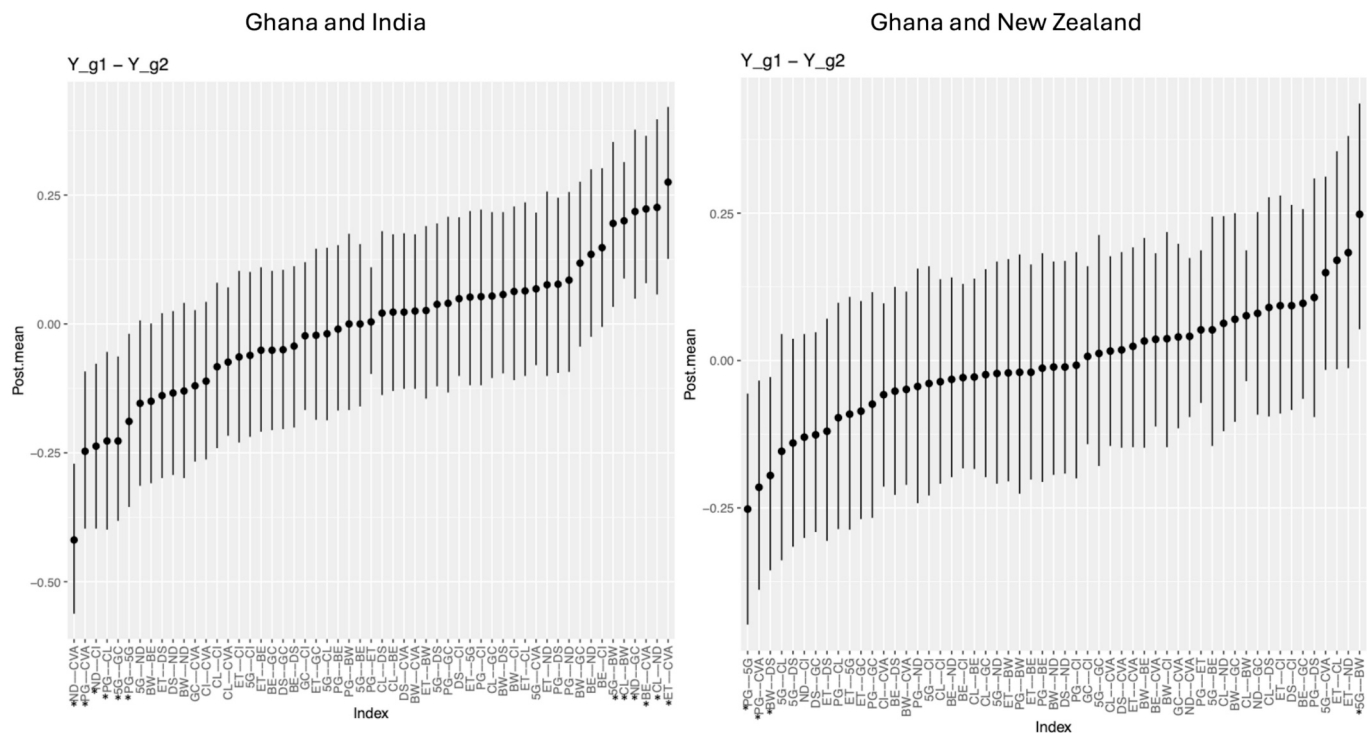


Fig. 2. Differences for each node-to-node association between Ghana and India (left), and Ghana and New Zealand (right). Dots show mean difference between the countries for each association, error bars show 95 % CIs for this difference using 5000 posterior estimates. Associations with CIs that do not include zero are with an asterisk and deemed to be statistically significantly between the countries. *Note:* PG = God’s punishment belief, ET = end times belief, 5G = 5G internet technology belief, CL = COVID-19 created in lab belief, BW = bioweapon belief, BE = bat eating belief, DS = deliberately spread belief, ND=COVID-19 not harmful belief, GC = genetic change belief, CI=COVID-19 vaccine cause infertility belief, CVA = COVID-19 vaccination attitudes.

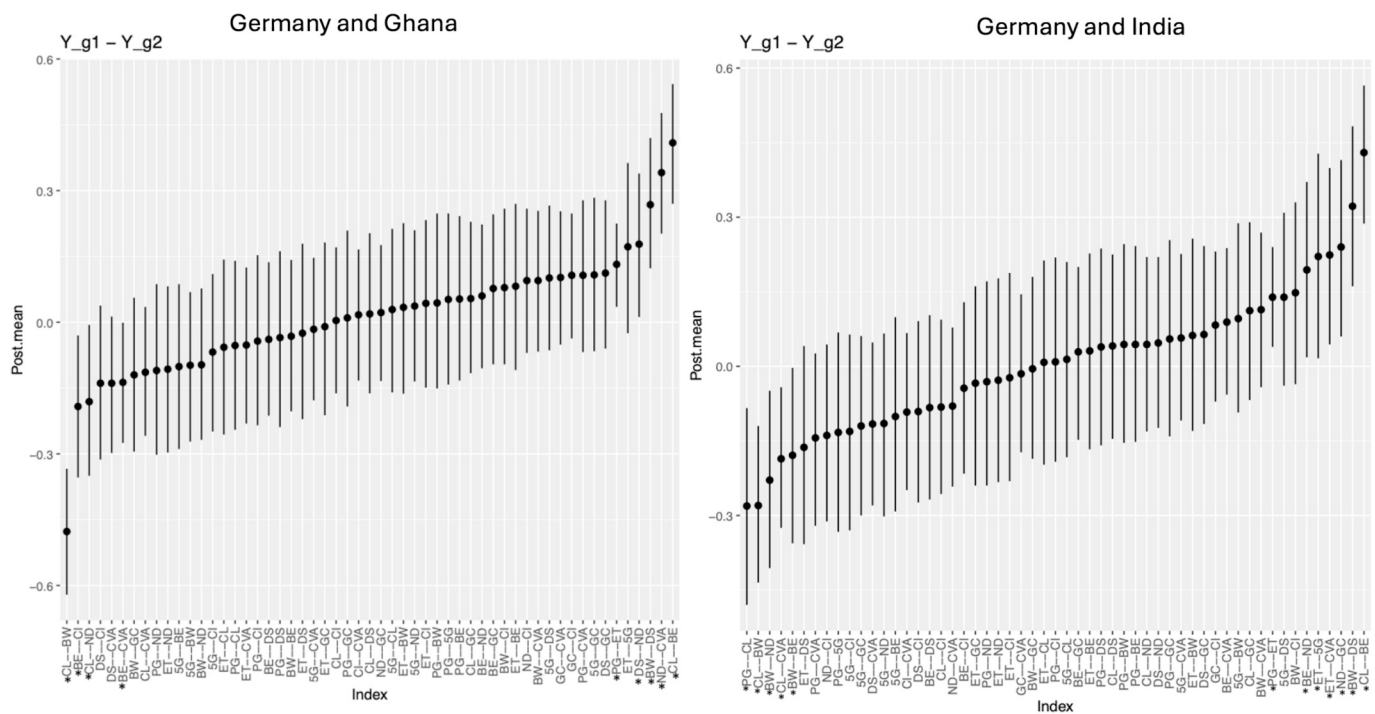


Fig. 3. Differences for each node-to-node association between Germany and Ghana (left), and Germany and India (right). Dots show mean difference between the countries for each association, error bars show 95 % CIs for this difference using 5000 posterior estimates. Associations with CIs that do not include zero are with an asterisk and deemed to be statistically significantly between the countries. *Note:* PG = God’s punishment belief, ET = end times belief, 5G = 5G internet technology belief, CL = COVID-19 created in lab belief, BW = bioweapon belief, BE = bat eating belief, DS = deliberately spread belief, ND=COVID-19 not harmful belief, GC = genetic change belief, CI=COVID-19 vaccine cause infertility belief, CVA = COVID-19 vaccination attitudes.

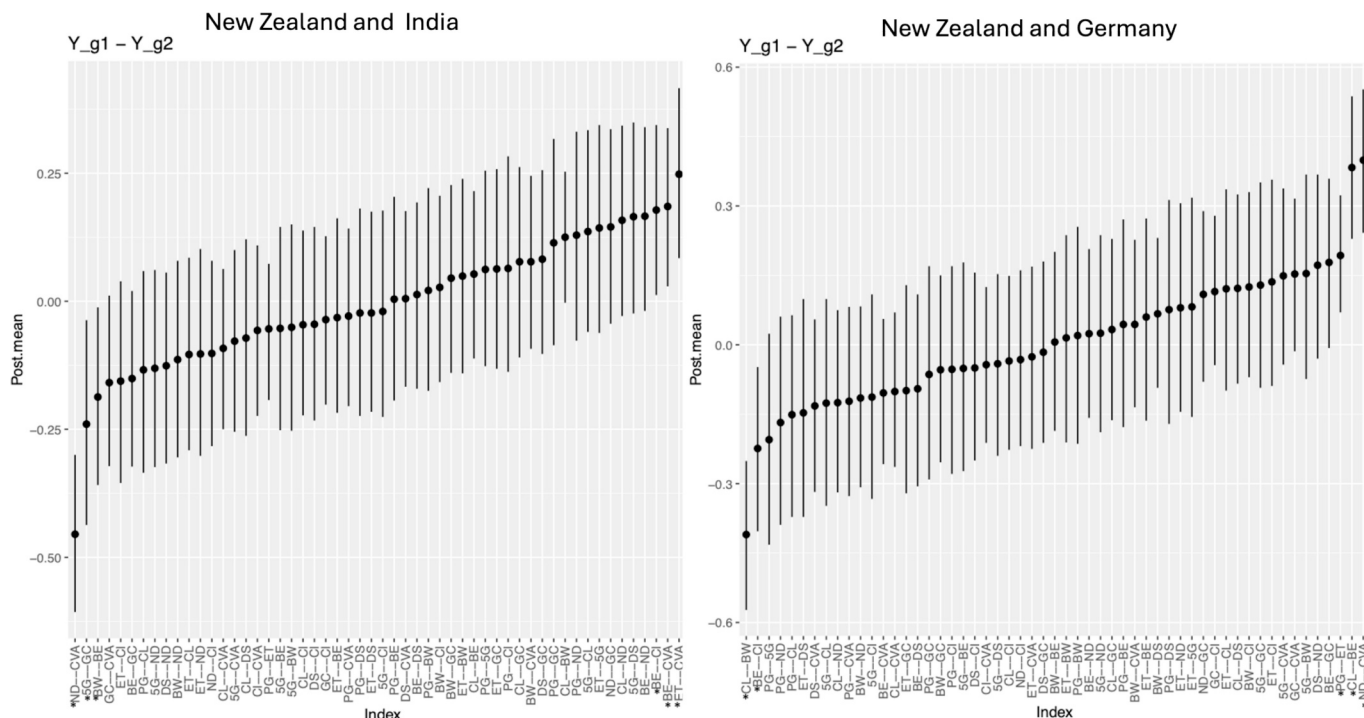


Fig. 4. Differences for each node-to-node association between New Zealand and India (left), and New Zealand and Germany (right). Dots show mean difference between the countries for each association, error bars show 95 % CIs for this difference using 5000 posterior estimates. Associations with CIs that do not include zero are with an asterisk and deemed to be statistically significantly between the countries. *Note:* PG = God’s punishment belief, ET = end times belief, 5G = 5G internet technology belief, CL = COVID-19 created in lab belief, BW = bioweapon belief, BE = bat eating belief, DS = deliberately spread belief, ND=COVID-19 not harmful belief, GC = genetic change belief, CI=COVID-19 vaccine cause infertility belief, CVA = COVID-19 vaccination attitudes.

–0.23; Fig. 1: Supplementary Table S1). This relation was found to be within the 95 % CI in this context compared to New Zealand, Germany, and Ghana (Figs. 2, 3 and 4). The belief that COVID-19 was created in a lab was positively and uniquely linked to COVID-19 vaccination attitudes (*weight edge* = 0.18; Fig. 1: Supplementary Table S1), exhibiting the sufficient 95 % CI when compared to the German sample only (Figs. 2, 3 and 4). The belief that COVID-19 pandemic was deliberately created to install 5G technology linked negatively and independently to COVID-19 vaccination attitudes in New Zealand only (*weight edge* = –0.16). This relation did not fall within the 95 % CI compared to all the other countries (Figs. 2, 3 and 4). The links between the infodemics and attitudes towards COVID-19 vaccination among the German sample did not fall within the 95 % CI.

3.3. Predictability

In Germany, beliefs attributing the COVID-19 pandemic to Chinese bat consumption and as a divine punishment were most influential (Fig. 5 illustrates the predictability plots). Conversely, in Ghana, beliefs about COVID-19 as a bioweapon and a divine punishment held the most significant impact. Among the New Zealand sample, beliefs in the deliberate COVID-19 spread and the installation of 5G technology were the most influential variables. In India, beliefs concerning COVID-19 as an apocalypse and divine punishment were the most influential variables (Supplementary Table S2).

4. Discussion

To comprehensively understand the influence of infodemics on the COVID-19 pandemic, we conducted an online cross-sectional study to examine the complex interrelatedness between COVID-19-related infodemics and attitudes towards COVID-19 vaccination across four geographically diverse countries employing the novel network analysis

methodology. We found that in India, the apocalypse belief related to less favorable attitudes towards COVID-19 vaccination attitudes, compared to all the other countries. Of note, this apocalypse belief emerged as the most influential node in this context as well. However, the positive link between the belief that COVID-19 originated from a lab and COVID-19 vaccination attitudes in this context was significant when compared to Germany. The positive link between the belief that COVID-19 is divine punishment for humanity’s sins and COVID-19 vaccination attitudes was unique in Indian and New Zealand compared to the Ghanaian sample.

Compared to India and Germany, the belief that COVID-19 is not harmful was significantly linked to less favorable COVID-19 vaccination attitudes in New Zealand. This association was particularly significant in Ghana compared to India. Compared to the German and Indian samples, the belief that COVID-19 pandemic originated from Chinese consumption of bat meat and its link to favorable attitudes towards COVID-19 vaccination was noticeable in Ghana, while this relation was significant in New Zealand compared to the Indian sample. Notably, the observed differences in the results may be due to variations in sample characteristics arising from differing recruitment strategies across the countries. These differences may not fully reflect true cross-country variations in the relations between infodemics and vaccination attitudes. Moreover, the most influential beliefs varied across the countries. In Germany, the bat consumption related infodemic was prominent. In Ghana, the infodemic linked to bioweapon was noticeable. In India, the infodemic surrounding the apocalypse belief was most influential. New Zealand highlighted concerns related to 5G technology. Across all countries, there were consistent strong positive connections between the infodemics.

The apocalypse infodemic and less favorable attitudes towards COVID-19 vaccination in India may be influenced by cultural perceptions and religious interpretations, which shape how individuals perceive events, including diseases [44]. In highly religious cultures

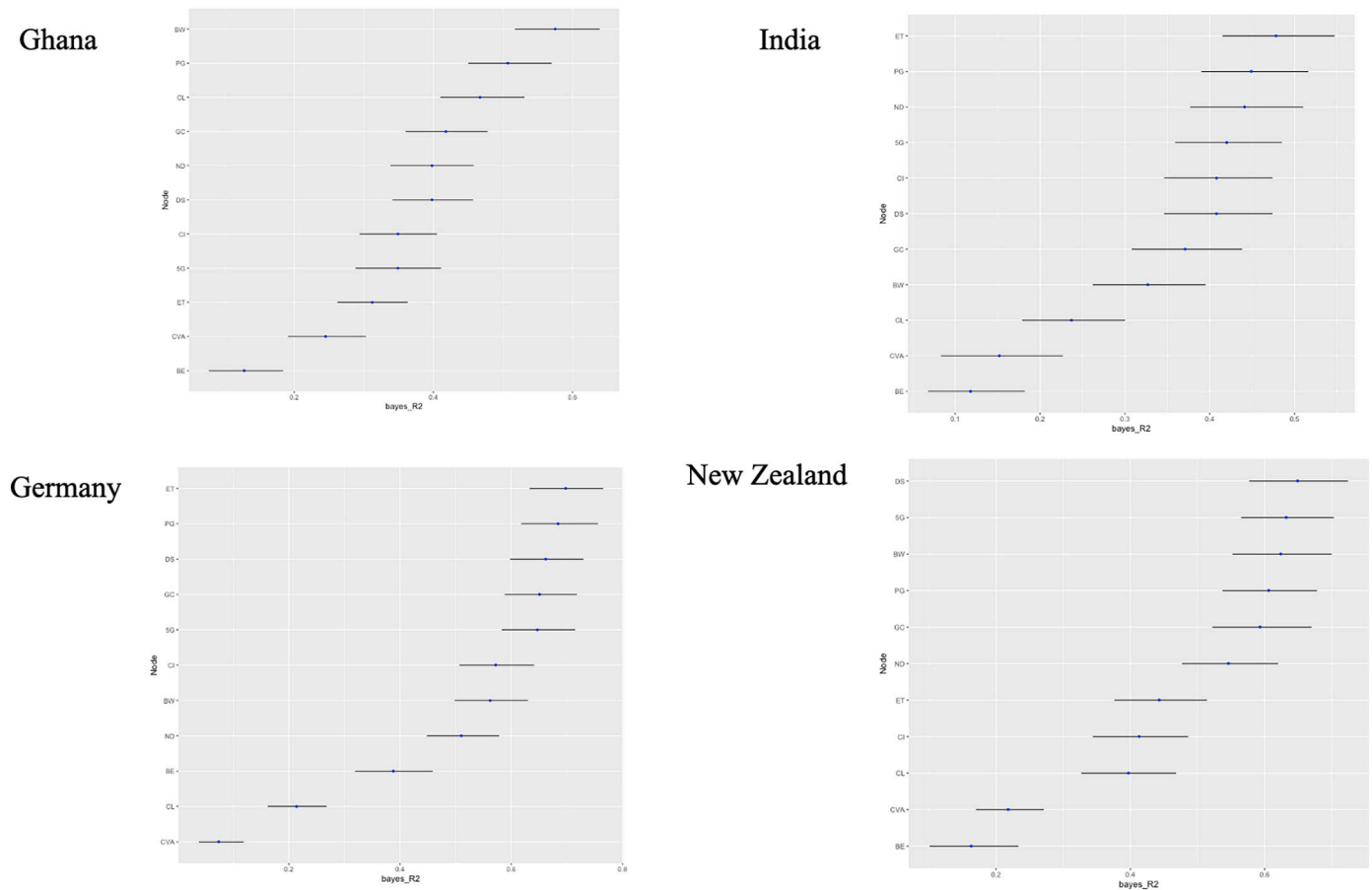


Fig. 5. Bayesian gaussian graphical models predictability plots of the relation between the COVID-19 infodemics, and COVID-19 vaccination attitudes only associations which 95 % credible interval did not include zero were printed. Note: PG = God’s punishment belief, ET = end times belief, 5G = 5G internet technology belief, CL = COVID-19 created in lab belief, BW = bioweapon belief, BE = bat eating belief, DS = deliberately spread belief, ND=COVID-19 not harmful belief, GC = genetic change belief, CI=COVID-19 vaccine cause infertility belief, CVA = COVID-19 vaccination attitudes.

such as India, there is a tendency to attribute health issues to spiritual factors [35,45]. Religious beliefs often shape how individuals interpret and find meaning in tragedies and events, as seen during the COVID-19 pandemic [46]. Some individuals with religious beliefs may perceive COVID-19 as a sign of the end of humanity and adopt a fatalistic and conspiratorial attitude towards preventive measures such as vaccination, as they believe the course of events is predetermined and efforts to control the virus are futile [47,48]. Similar to our findings, Dein [46] reported that individuals believed that COVID-19 represents a rapture of the faithful into heaven, with those remaining on earth facing eternal condemnation. Notably, the apocalypse belief emerged as the most influential variable in this context.

The positive link between the belief that COVID-19 is a punishment from God and COVID-19 vaccination attitudes in India and New Zealand suggests that individuals who perceived the pandemic as a form of divine punishment were more likely to exhibit favorable attitudes towards COVID-19 vaccination. While this finding contrasts previous research conducted in Africa, Europe, and the Middle East [47,49], this could be due to differences in contexts across these studies, especially considering the cultural influences on infodemics [25]. Possible reasons could be that individuals who view COVID-19 as divine punishment may see vaccination as a means of protecting themselves from further divine retribution. In this context, religious interpretations of the pandemic can act as a coping mechanism. Evidence suggests that during challenging times, people often turn to religion for solace and explanations, which can foster favorable attitudes towards COVID-19 vaccination [50]. This perspective further implies that while individuals may recognise the belief in divine punishment, they remain motivated to take proactive,

human measures to alleviate their suffering. Supporting this, a review reported a positive association between religious-related infodemics and willingness to accept COVID-19 vaccination [3,9].

Individuals who believe that COVID-19 originated from a lab or from Chinese consumption of bats may acknowledge the existence of the virus and may perceive themselves as susceptible to it. This heightened threat perception could have motivated a stronger desire to protect oneself, leading to more favorable attitudes towards vaccination as a means of mitigating the perceived risk [3,51]. This explains the observed direct links between the lab and bat-eating related infodemics, and COVID-19 vaccination attitudes in India, Ghana, and New Zealand. Likewise, Yang et al. [52] found that infodemics related to the origins of COVID-19 did not impact vaccine hesitancy. In contrast, infodemics related specifically to COVID-19 vaccines, such as the belief that the vaccines were fabricated by pharmaceutical companies for profit, had a more significant effect on increasing vaccine hesitancy. These potential patterns in findings could imply that while beliefs about the COVID-19 virus origin might enhance vaccination coverage by increasing perceived threat, infodemics directly targeting the vaccines themselves tends to undermine vaccination efforts [53]. Notwithstanding, the punishment from God, lab creation, and bat consumption related infodemics have been found to negatively impact other health outcomes such as mental health during the pandemic [32]. This diverse impact of infodemics signifies their complex role in influencing health and well-being, underscoring the importance of addressing infodemics in effective pandemic, epidemics, and Pathogen X eradication strategies.

Studies have also reported that perceiving the COVID-19 pandemic as not harmful was associated with less favorable attitudes towards

COVID-19 vaccination [3,54], which concurs with our results found from the New Zealand sample. Unsurprisingly, research has consistently reported positive links between perceived severity of a disease and positive health outcomes [55]. Notably, efforts to prevent other infectious diseases such as the influenza, Ebola, and HIV have also faced related infodemics [56].

Moreover, the most influential infodemics, such as the bioweapon, 5G technology, apocalypse, and bat consumption beliefs in Ghana, New Zealand, Germany, and India, respectively, suggest that the influences of these beliefs were largely explained by their relations with other variables [24]. These were some of the most common reported infodemics during the COVID-19 pandemic [3]. The strong positive relation between the infodemics suggest that they may reinforce each other and thus complicate different efforts to promote vaccination and achieve overall well-being during pandemics, epidemics, and Pathogen X outbreaks.

4.1. Strengths and limitations

Our study is unique due to its exploration of the complex impact of infodemics on COVID-19 vaccination across four countries from different continents, utilizing the novel network analysis. This cross-country comparison enhances the external validity and generalisability of our findings. The use of stability estimates, such as bootstrapping techniques, ensured that the results are robust and not unduly influenced by sampling variability. This enhances the validity, reliability, and interpretability of the current results, providing greater confidence in the generalisability of the findings. Hence, the risk of drawing misleading conclusions from random fluctuations in the sample is reduced, strengthening the overall conclusions from network analysis. Additionally, our research makes a significant contribution to the limited literature in sub-Saharan Africa (i.e., Ghana), an underrepresented region in this field of research. The findings offer valuable insights into the similarities and differences in the infodemics-COVID-19 vaccination attitudes links across countries, supporting effort towards understanding vaccine acceptance.

The study limitations include the use of a convenience sampling technique, which may not be representative of the population of each country as this method relies on available participants. There were also differences in the sampling techniques, which warrant caution when interpreting the cross-country differences in the results, as these may have been partially influenced by variations in sample characteristics. Further, there is a potential bias from using online surveys, as only individuals with internet access participated [57]. Additionally, the samples were unmatched. The cross-sectional design prevents the establishment of causation, and self-report measures may lead to biased responses, such as socially desirable and moderation answers [58]. Furthermore, the lack of sufficient confidence in the association between the infodemics and attitudes towards COVID-19 vaccination among the German sample could be due to limited statistical power to establish such links. Alternatively, it is also possible that vaccination attitudes are influenced by other factors in this developed context, such as the stringent enforced laws.

4.2. Implications and future directions

While we observed the positive impact of some infodemics on vaccination attitudes in our study, we also acknowledge their negative impacts on other health outcomes as reported in the literature. Thus, our findings, combined with the existing evidence, suggest that for the purposes of overall well-being, including higher vaccination coverage, efforts to address infodemics during pandemics, epidemics, and Pathogen X outbreaks could be essential. Strategies include: first, exposing individuals to a version of already known infodemics, which they can refute, a process known as psychological inoculation. This process has been found to be effective in combating infodemics [59,60]. Such a

strategy could target the most influential variables, as changes in these variables could lead to a ripple effect on other variables, according to our predictability estimates. Secondly, an experimental study demonstrated that when individuals were provided with expert information it corrected their beliefs about the COVID-19 pandemic [61]. It is important to plan scientific knowledge-based public education initiatives that consider each society's cultural, social, economic, religious, and local characteristics. The media could be motivated to communicate such knowledge to the public [62]. Future research could focus on establishing causal relations among these variables. Studies should triangulate the current findings using a more representative sampling method among diverse cultures and sub-groups. Researchers could incorporate various infectious diseases and research approaches, such as the sequential exploratory mixed method [63], to ethnographically unravel the different infodemics and their impact on vaccination. Such an approach would provide a further and deeper understanding of the dynamics involved in promoting high vaccination coverage and inform more effective strategies for addressing infodemics.

5. Conclusion

The current study found that in India, the apocalyptic belief negatively related to COVID-19 vaccination attitudes compared to the other countries. In New Zealand and Ghana, the belief that COVID-19 is not harmful negatively impacted attitudes towards COVID-19 vaccination. COVID-19 origin-related beliefs showed positive links between infodemics and COVID-19 vaccination attitudes in Ghana and New Zealand, compared to India and Germany. The most influential infodemics varied by country: bioweapon belief in Ghana, 5G technology belief in New Zealand, end times belief in India, and bat consumption belief in Germany. Our results suggest that country-specific infodemics have a significant impact on COVID-19 vaccination attitudes, with notable variations observed between countries, emphasising the need for tailored public health interventions to address local infodemics dynamics effectively during pandemics, epidemics, and Pathogen X outbreaks.

Ethics approval and consent to participate

The study was approved by the institutional Human Research Ethics Committee of Victoria University of Wellington, Wellington, New Zealand (#0000029770). The study was in line with the Declaration of Helsinki, which outlines fundamental ethical principles for health research involving the use of human participants [64]. Participants freely gave informed consent to participate in this study and for their results to be published or used for other academic purposes such as reports, presentations, and public documentation in aggregate form (i.e., a combined data analysed with those of others).

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CRediT authorship contribution statement

Peter Adu: Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Tosin Popoola:** Writing – review & editing, Supervision, Conceptualization. **Naved Iqbal:** Writing – review & editing, Data curation. **Anja Roemer:** Writing – review & editing, Validation, Methodology, Data curation. **Oleg N. Medvedev:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Colin R. Simpson:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.vaccine.2025.126733>.

Data availability

Data will be made available on request.

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