## Postpartum Haemorrhage 2

# Prevention of postpartum haemorrhage: from evidence to implementation at scale

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**Postpartum haemorrhage (PPH) is a leading cause of maternal death. Preventing PPH can spare women from experiencing the trauma and risks of PPH, reduce the strain on overstretched health systems, and probably produce better outcomes than a strategy solely focused on PPH treatment. Prevention of PPH is often interpreted as provision of uterotonic drugs to contract the uterus at the time of childbirth. Although uterotonics are a central strategy for PPH prevention, several other approaches can prevent PPH or ameliorate its severity. These approaches include addressing the unmet need for contraception, remedying anaemia and other modifiable risk factors for PPH, optimising medical conditions that predispose to PPH, and tackling the rise in caesarean births in many countries. Effective delivery of preventive care requires early and regular antenatal care and planned birth at appropriately resourced health facilities. Social and behavioural change interventions for improving contraceptive provision and uptake, targeting adolescents, postpartum women, geographically remote communities, and families on low income, are a priority. Effective interventions to tackle anaemia include the management of heavy menstrual bleeding, pre-pregnancy or antenatal haemoglobin testing and oral or intravenous iron treatment, dietary improvements, and—on rare occasions—blood transfusion. Risk factors for PPH that need attention include high BMI, multiple pregnancy, gestational diabetes, pre-eclampsia, macrosomia, and several medical conditions. Caesarean births are associated with a substantial increase in PPH risk and should therefore only be done when medically indicated. A Cochrane network meta-analysis of 122 trials, with 121 931 women, found that the combinations of oxytocin plus misoprostol, or oxytocin plus ergometrine, were the most effective prophylaxis for PPH when given at the time of childbirth; however, these combinations had a higher risk of side-effects compared with single-drug prophylaxis. Oxytocin and carbetocin were the most effective single drugs for PPH prophylaxis, with minimal side-effects. Single uterotonic prophylaxis with either oxytocin or carbetocin is, therefore, recommended for routine prophylaxis. However, if oxytocin or carbetocin is not accessible, misoprostol is an alternative. Combination prophylaxis with oxytocin plus misoprostol can be considered for women at high risk of PPH. Ergometrine alone and oxytocin plus ergometrine combination are no longer recommended due to hypertension-related safety concerns. A robust implementation approach that engages various stakeholders to promote change, ensures the supply of quality-assured medicines and devices, provides training and support, and secures ongoing political and financial commitment is necessary to translate evidence into global impact.**

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## Introduction

Progression from an uncomplicated birth to a life-threatening postpartum haemorrhage (PPH) is often unpredictable and rapid, frightening and risky for the woman, and demanding for the health-care providers and health system. Furthermore, even the most effective medical and surgical treatment of PPH by highly skilled providers does not guarantee successful outcomes. Therefore, primary prevention of PPH through effective strategies is the ideal goal. Although all instances of PPH cannot be eliminated through preventive strategies, many effective interventions can reduce the chance of a woman having a PPH or diminish its severity and consequences.

Prevention of PPH is often given a narrow focus, with an emphasis on the use of a uterotonic drug to contract the uterus after childbirth. However, such a narrow focus misses several other opportunities to prevent PPH, as highlighted in the first paper in this Series.[1] We therefore take a broad perspective on prevention in this second paper, to include interventions targeting menstrual health (eg, addressing heavy menstrual bleeding to reduce the risk of anaemia in at-risk populations) and reproductive health (eg, meeting the unmet need for contraception), as well as pre-pregnancy, pregnancy, labour and childbirth, and postpartum periods (panel 1).[1]

The preventive steps outlined in this Series paper should be understood in the broader context of the social, economic, structural, and political determinants of health. A health facility that is aiming to prevent PPH with the use of high-quality uterotonic prophylaxis will bring no benefit to a woman who does not have the autonomy, knowledge, or means to seek health care (ie, the first and second delays of the three delays model:[7] delay in deciding to seek care and delay in reaching a health facility). Furthermore, an under-resourced and poorly supported health service might not have cold-chain maintenance for oxytocin injections, or the necessary staff to administer the preventive intervention (ie, the final delay in the three delays model:[7] delay in receiving effective care).

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***Panel 1:*** **Search strategy and consensus-building consultations**

The recommendations are based on published systematic reviews of the current literature, appraisal of professional body guidelines, and expert group discussions. For the systematic review on causes and risk factors of postpartum haemorrhage, we searched MEDLINE, Web of Science, Embase, Cochrane Library, and Google Scholar (last search Nov 30, 2024).[2] We also refer to the latest updated Cochrane network meta-analysis on uterotonic agents for preventing postpartum haemorrhage.[3] For the review of professional body guidelines, we reviewed the latest WHO–International Federation of Gynecology and Obstetrics–International Confederation of Midwives consolidated guidelines for the prevention, diagnosis, and treatment of postpartum haemorrhage,[4] WHO's comprehensive framework for action in accelerating anaemia reduction,[5] and the Royal College of Obstetricians and Gynaecologists guideline for the diagnosis and management of placenta praevia and placenta accreta.[6] For expert group meetings, recommendations were formulated based on an international consensus meeting on postpartum haemorrhage held in March, 2023, with a group of 27 key stakeholders from Argentina, Brazil, Kenya, Malawi, Nigeria, Norway, Pakistan, South Africa, Sri Lanka, Tanzania, the UK, and the USA. Agreements were reached through consensus.

Preventive strategies should therefore be supported with contextually appropriate implementation approaches and resources, and integrated into the community and health system, to achieve sustained global benefit. To facilitate evidence-based PPH prevention, we provide various clinical and policy recommendations and highlight potentially important implementation approaches throughout this Series paper.

## Addressing the unmet need for contraception

Women who avoid unwanted or unintended pregnancies by accessing contraception can also avoid pregnancy complications such as PPH. Many women, particularly in low-income and middle-income countries, have unintended pregnancies due to inadequate access to contraception.

The estimated global unmet need for contraception in 2019 was 162·9 million (95% uncertainty interval 155·6–170·2), out of the 1·2 billion women who had a need for contraception.[8] The global unmet need rate was 8·3% (8·0–8·7), but this average hides important disparities; for example, the unmet need in western Europe is 3·5% (3·2–3·8), but 9·3% (8·0–10·6) in south Asia and 18·0% (17·6–18·4) in sub-Saharan Africa.[8]

The unmet need for contraception worldwide has substantially reduced since 1990. However, the use of modern contraceptive methods differs between high-income and low-income countries.[9] Analysis of the best-performing countries (ie, the positive outliers or the exemplars) in each region is likely to give important and contextually relevant insights on how to reduce the unmet need for contraception. Strategies to address unmet need should be based on a sound understanding of the needs and preferences of women and their communities. Social and behavioural change interventions for improving contraceptive provision and uptake, targeting adolescents, postpartum women, geographically remote communities, families on low income, people with disabilities, and people living in fragile settings, are a priority.[10] Immediate postpartum contraception (within 24 h) should be promoted to meet contraceptive need and achieve a desirable interpregnancy interval. Potentially useful strategies for meeting the unmet need for contraception include community engagement, free or subsidised contraceptives, increasing girls' and boys' access to reproductive and sexual health education, task sharing or shifting to expand the range of front-line health providers who can offer contraceptive services,[11] leveraging immunisation services to offer contraceptive options, behaviour change strategies for health providers to promote contraception, mass media campaigns, and mobile services.[10] Continued global and national investment in contraceptive coverage will bring many benefits, including a reduction in PPH occurrences and deaths.

## Mitigating risk factors for postpartum haemorrhage

There are several sociodemographic, medical, and pregnancy-related risk factors for PPH (panel 2),[1] many of which are modifiable. Many risk factors also contribute to other complications in pregnancy or general ill health in women, and therefore need attention. Examples of such risk factors include anaemia, high BMI, gestational diabetes, and hypertensive disorders of pregnancy.[1,4] Two strong risk factors that require urgent global action are anaemia and caesarean sections that are not medically indicated.

### Anaemia

Anaemia in pregnancy is defined as a haemoglobin concentration (Hb) of less than 110 g/L in the first and third trimesters, or less than 105 g/L in the second trimester.[4] The global prevalence of anaemia in pregnancy is 37%; however, regions vary considerably, with Africa and Asia having the highest prevalance.[16,17] The main cause of anaemia is iron deficiency, which is often secondary to dietary deficiency or heavy menstrual bleeding.[16] Other important causes of anaemia, such as haemoglobinopathies, malaria, and hookworm infestation, should also be considered depending on the geographical setting and clinical context.

Anaemia is strongly associated with PPH (adjusted odds ratio [OR] 2·36, 95% CI 1·29–4·32).[2] This association could be due to compensatory increases in cardiac output;

placental size and vascularity;[18] reductions in the oxygen carrying capacity of blood, compromising myometrial contractility;[19] and impaired blood clotting. Anaemia is also strongly associated with the risk of maternal death. An analysis of more than 310 000 women with severe anaemia (defined as Hb <70 g/L) from 359 health facilities in 29 countries found that the odds of death in women with severe anaemia were more than two-fold higher compared with women without severe anaemia (adjusted OR 2·36, 1·60–3·48).[20] Other important implications of anaemia include infection, sepsis, low birthweight, preterm birth,[21] and social and economic impacts, including a reduced ability to engage in paid work, increased gender wage gaps, and greater risk of household poverty.[5,22]

A full blood count is the optimal test for diagnosing anaemia.[4] However, in settings where this is not available, on-site haemoglobin testing with a haemoglobinometer is recommended.[4] Development of scalable, low-cost, on-site, and accurate haemoglobin testing technology is a research priority.

Effective interventions to tackle anaemia include the management of heavy menstrual bleeding, dietary adjustments, oral or intravenous iron treatment, and, on rare occasions, blood transfusion. Dietary improvements should focus on a balanced diet enriched with foods high in iron, such as leafy vegetables, pulses, eggs, dairy, fish, and meat, as well as minimising the intake of iron chelators (eg, tea). Heavy menstrual bleeding can be treated with the combined oral contraceptive pill, non-steroidal anti-inflammatory drugs, tranexamic acid, or an intrauterine hormone-releasing system.[23] Prevention and treatment of hookworm infection in endemic areas and malaria treatment in pregnancy are also important strategies to reduce the risk of anaemia.[5]

WHO recommends routine daily iron and folic acid supplementation for all pregnant women, with 30–60 mg of elemental iron and 400 µg of folic acid.[4] However, if a woman is diagnosed with anaemia during pregnancy, the elemental iron dose should be increased to 120 mg per day until her Hb reaches at least 110 g/L.[4] Intravenous iron infusion can be considered when oral iron is not tolerated or ineffective in treating the anaemia, or when anaemia needs to be corrected rapidly (eg, when severe anaemia is diagnosed close to the time of birth).[4] However, as there is a small risk of anaphylaxis with iron infusion (estimated to be <1 in 1000),[24] this treatment should only be offered in facilities that can monitor for and manage anaphylaxis.

## Caesarean sections that are not medically indicated

A caesarean section can be a life-saving intervention for women and their newborns when conducted at the right time and for the right indication, by skilled health-care providers. However, many caesarean sections are done without a clear medical indication, and many are not done despite being needed, or done late.[25] The overuse and underuse of caesarean sections vary hugely in regions, and between and within countries.[25] The caesarean section rate in many sub-Saharan countries is less than 5%, whereas in many Latin American countries, this rate exceeds 50%.[26] A strict benchmark for an appropriate caesarean birth rate for a country is difficult to define as it is dependent on various factors, including population and health service characteristics, but a

### *Panel 2:* Risk factors for postpartum haemorrhage

**Risk factors with strong association (OR >2)**

- Anaemia
- Female genital mutilation
- Sepsis
- Previous PPH
- Grand multiparity
- No antenatal care
- Placenta praevia
- Resolved placenta praevia
- Stillbirth
- Multiple pregnancy
- Assisted conception
- Caesarean birth
- General anaesthesia[12]
- Magnesium infusion[13]
- Prolonged second stage of labour[14]
- Shoulder dystocia
- Birthweight ≥4500 g

**Risk factors with moderate association (OR >1·5 to 2)**

- BMI ≥30 kg/m²
- Liver disease
- Family history of PPH
- Hypertensive disorders of pregnancy[13]
- Pre-eclampsia
- Gestational diabetes
- Polyhydramnios
- Birthweight 4000 g to <4500 g
- Episiotomy[13]
- COVID-19

**Risk factors with weak association (OR >1 to 1·5)**

- BMI 25–29·9 kg/m²
- Black ethnicity
- Asian ethnicity
- Uterine fibroids
- Antidepressant use
- Asthma
- Epilepsy[15]
- Premature rupture of membranes
- Induction of labour
- Augmentation of labour
- Instrumental birth

Information sourced from Yunas et al,[2] or from other cited sources. PPH=postpartum haemorrhage. OR=pooled odds ratio (adjusted pooled ORs are reported, where available; otherwise, pooled crude ORs are reported).

caesarean rate that exceeds 20% is unlikely to be associated with benefits.[27] A *Lancet* Series on caesarean section, published in 2018, estimated that 6·2 million caesarean sections that were not medically indicated were conducted per year worldwide.[28]

Caesarean section is a strong risk factor for PPH (adjusted OR 5·18, 95% CI 3·42–7·85)[2] and also increases the future risk of further caesarean sections, uterine rupture, and placenta accreta spectrum, therefore increasing the risk of obstetric haemorrhage in future pregnancies. A systematic review found a quarter of all women who died in low-income and middle-income countries had undergone a caesarean section. Of these maternal deaths, a third were due to PPH.[29]

WHO has published evidence-based recommendations on reducing caesarean sections that are not medically indicated.[30] These recommendations include addressing women's fears and misperceptions about vaginal birth, mandatory second opinions for caesarean section indication, financial strategies to remunerate health professionals and facilities equally for vaginal births and caesarean sections, audits and feedback loops for facilities, and promotion of collaborative care models for midwives and obstetricians, in which intrapartum care is primarily provided by midwives.[30] Assisted vaginal birth and external cephalic version for breech pregnancies also have a role in reducing caesarean section rates. Although robust guidance is available, widespread implementation has not yet materialised. Urgent implementation research, including learning from positive outliers, is a priority.

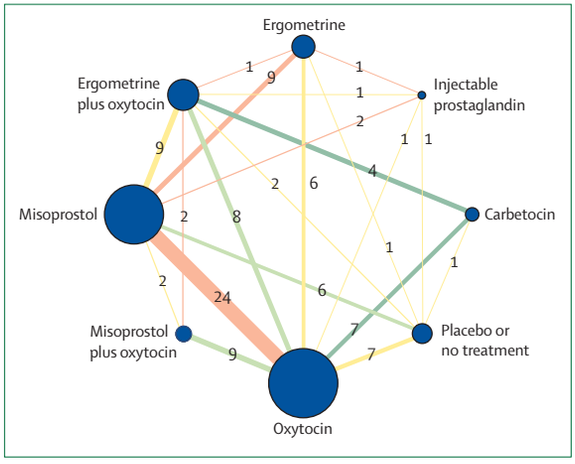


***Figure 1:*** **Network diagram of uterotonic drugs for the prevention of postpartum haemorrhage (blood loss ≥500 mL)**
Figure adapted from Gallos et al.[3] The nodes represent an intervention, and their size is proportional to the number of trials comparing this intervention to any other in the network. The lines connecting each pair of interventions represent a direct comparison; their width is proportional to the number of trials contributing to each direct comparison. Numbers on the lines represent the number of trials for each comparison. Dark green lines represent high-certainty evidence, light green lines are for moderate-certainty evidence, yellow lines are for low-certainty evidence, and red lines are for very low-certainty evidence.

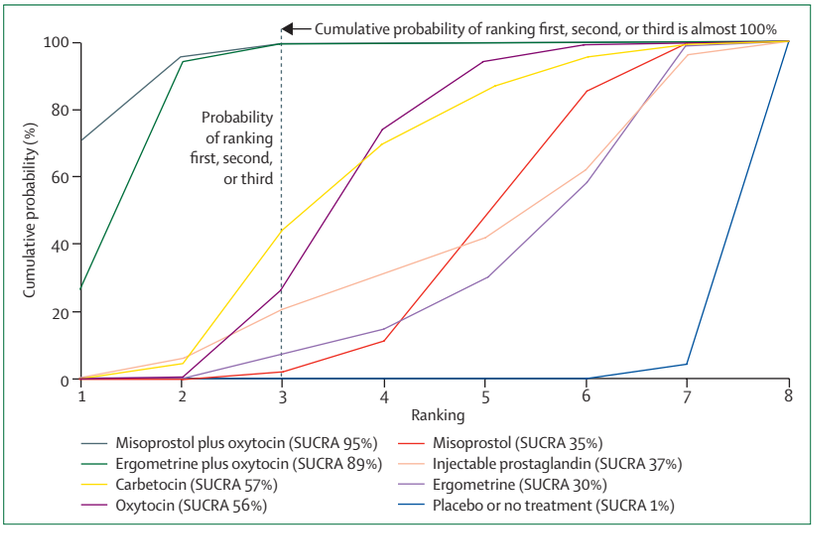


***Figure 2:*** **Cumulative rankograms comparing each of the uterotonic agents for prevention of postpartum haemorrhage (blood loss ≥500 mL)**
Figure adapted from Gallos et al.[3] Ranking indicates the cumulative probability of being the best agent, the second best, the third best (and so on). The x-axis shows the relative ranking and the y-axis the cumulative probability of each ranking. We estimate the surface underneath this cumulative ranking line (SUCRA); the larger the SUCRA, the higher its rank among all available agents.

## Routine uterotonic prophylaxis for all women

Uterine atony is reported in 70·6% of women diagnosed with a PPH (95% CI 63·9–77·3; n=834 707 women; 14 studies).[2] Although several risk factors for PPH are known, no accurate prediction models exist to foretell who will have a PPH, or, more specifically, atonic PPH.[31,32] Therefore, effective prevention of PPH with uterotonic drugs is advocated for all women after childbirth.[4] However, opinions differ over which uterotonic drug or drug combination is best for preventing PPH. A Cochrane network meta-analysis was conducted to explore the relative effects of various uterotonics and combinations thereof. The review included 122 trials (n=121 931 women) conducted across 48 high-income, middle-income, and low-income countries, involving seven uterotonic drugs or drug combinations (figure 1). Most studies were in hospital settings (115/122; 94%), with women having a vaginal birth (87/122; 71%).[3]

The network meta-analysis found that all drugs or drug combinations—except injectable prostaglandins, for which data were scarce—were effective in preventing PPH of at least 500 mL compared with placebo or no treatment. The two highest-ranked agents of all seven options were combinations of two uterotonic drugs: oxytocin plus misoprostol, and oxytocin plus ergometrine (figure 2). Oxytocin plus misoprostol reduced PPH (≥500 mL) by 30% when compared with oxytocin alone (risk ratio [RR] 0·70, 95% CI 0·57–0·87; moderate-certainty evidence), and oxytocin plus ergometrine reduced PPH (≥500 mL) by 24% when compared with oxytocin alone (RR 0·76, 0·64–0·90;

high-certainty evidence). The highest-ranked single agents were oxytocin and carbetocin, which were similar in their effectiveness in preventing PPH of at least 500 mL. Oxytocin reduced PPH by 42% when compared with placebo or no treatment (RR 0·58, 0·48–0·69) and carbetocin by 43%, again when compared with placebo or no treatment (RR 0·57, 0·43–0·74).[3] Misoprostol reduced PPH by 36% compared with placebo or no treatment (RR 0·64, 0·53–0·77), although evidence for this comparison was scarce.

The greater effectiveness of combination uterotonic prophylaxis, however, comes at a cost. Both oxytocin plus ergometrine and oxytocin plus misoprostol were associated with more side-effects compared with oxytocin alone. Oxytocin plus ergometrine was associated with vomiting, abdominal pain and diarrhoea, and hypertensive episodes;[3] oxytocin plus misoprostol was associated with fever, shivering, and diarrhoea.[3] Oxytocin and carbetocin had minimal side-effects.[3]

Health providers should consider the effectiveness and side-effects of uterotonic drugs for routine prophylaxis, as well as their cost, availability, feasibility of administration, acceptability, and impact on equity.[4] On the basis of these factors, oxytocin or carbetocin can be used as first-line agents for routine PPH prophylaxis at vaginal and caesarean births. However, because oxytocin degrades in heat, if cold-chain storage (2–8°C) cannot be guaranteed, heat-stable carbetocin would be the preferred option. If heat-stable carbetocin is unavailable or unaffordable, or injectable uterotonics are not feasible, oral misoprostol, which is heat-stable, is an alternative.[4] Prophylactic uterotonic drugs should be given immediately (preferably within 1 min) after birth.

The recommended dose of oxytocin for PPH prophylaxis is 10 international units, given intramuscularly or intravenously.[4] Intravenous administration can be more effective and is therefore recommended if the woman already has an intravenous line; however, rapid bolus infusion of oxytocin should be avoided due to the risk of hypotension. The recommended dose of carbetocin for PPH prophylaxis is 100 µg, given intramuscularly or intravenously.[4] The recommended dose for misoprostol is 400 µg, given orally.[4]

### Combination uterotonic prophylaxis for women at high risk of postpartum haemorrhage

The Cochrane network meta-analysis of uterotonics found that, when compared with oxytocin alone, the combination of oxytocin plus misoprostol is more effective in preventing PPH of at least 500 mL (35 fewer PPHs per 1000 women), and in reducing blood transfusion (13 fewer per 1000), the need for additional uterotonics for PPH treatment (55 fewer per 1000), and blood loss (60 mL less on average).[3] The combination of oxytocin plus ergometrine is more effective in preventing PPH of at least 500 mL (28 fewer PPHs per 1000 women), and in reducing blood transfusion (six fewer per 1000) and the need for additional uterotonics (40 fewer per 1000), when compared with oxytocin alone. Although these combination regimens are not routinely recommended due to the risk of side-effects and potential complications, the risk–benefit balance should be considered for women at high risk of PPH, for whom combination uterotonic prophylaxis might carry more benefit than harm. WHO therefore suggests that the combination of oxytocin and misoprostol be considered for prophylaxis in women at high risk of PPH.[4] The combination of oxytocin and ergometrine is not recommended due to the risks this regimen poses to women with known or unknown hypertension. We suggest that the combination regimen of oxytocin and misoprostol be considered for those with risk factors, particularly if the association with such risk factors is strong, or if they have multiple risk factors[1]—situations where the potential benefits could outweigh the potential risks (panel 3).

Tranexamic acid is an important drug in the treatment of PPH (see the third paper in this Series[33]). However, two recent Cochrane reviews have shown that tranexamic acid does not have a preventive role.[34,35] The risk of thromboembolic events is potentially increased with tranexamic acid use, and this risk probably outweighs the theoretical benefit of tranexamic acid in PPH prevention, particularly for caesarean birth, for which the baseline risk of thromboembolism is increased.[4] Furthermore, the likelihood of serious medication errors with inadvertent intrathecal injection of tranexamic acid (mistaken for spinal anaesthetic drugs) can increase with widespread, but medically unindicated, use of this drug.[36,37]

### Preventing placenta accreta spectrum

Placenta accreta occurs when the placenta invades deeply into the uterine wall, making it difficult for the placenta to detach from the uterus after childbirth. Attempts to separate the adherent placenta can result in catastrophic bleeding. Although its cause is not fully understood, a

**_Panel_ 3: Priority interventions at scale for postpartum haemorrhage prevention**

- Address the unmet need for contraception
- Improve antenatal care coverage
- Mitigate modifiable risk factors for PPH (eg, high BMI and hypertensive disorders)
- Diagnose and address anaemia
- Ensure women at high risk of PPH give birth at appropriate facilities
- Reduce caesarean sections that are not medically indicated
- Take steps to reduce the prevalence of placenta accreta
- Offer single uterotonic prophylaxis for all births
- Consider combination uterotonic prophylaxis for women at high risk of PPH

PPH=postpartum haemorrhage.

commonly accepted mechanism postulates the destruction of the endometrium (eg, during a previous caesarean section, uterine curettage, or myomectomy), predisposing women to deeper invasion of the placenta into the uterine muscle.[38] Rates of placenta accreta are rising rapidly worldwide, in parallel with the global rise in caesarean section rates.

The primary preventive strategy for addressing PPH related to placenta accreta spectrum is to curb the increase in caesarean sections that are not medically indicated. Ultrasound placental localisation should be routine care for all women, particularly for those who have had a previous caesarean section. However, an ultrasound scan might not always detect placenta accreta spectrum, and a high index of suspicion should be maintained even when the scan is normal.

If ultrasound shows invasion of placenta into a uterine scar, several steps should be taken for PPH prevention, based on evidence-based guidance[39] and senior obstetric involvement. Preoperative planning—particularly imaging to identify any involvement of the bladder, cervix, parametrium, or bowel—and rapid escalation from a caesarean section to hysterectomy to prevent excessive blood loss are important preventive strategies for PPH from placenta accreta spectrum. Such care is best delivered at a tertiary hospital with expert multidisciplinary care, blood and blood products, and intensive care facilities. Prophylactic uterine artery embolisation, or leaving the placenta in situ for natural resolution, are steps that can be considered in specialist facilities with appropriate expertise.[6]

### Implementation at scale

Guidelines alone are insufficient to ensure implementation of PPH prevention measures at scale. Policy environments that include appropriate financing structures, reliable procurement and supply chains for essential drugs and equipment, supportive workforce models (eg, midwifery-led care), and auditing and accountability systems are necessary for effective implementation, together with commitment from political, policy, practitioner, and community stakeholders; institutional readiness with trained and motivated staff; adequate and sustained financing; and advocacy.[40] Strong national leadership to establish clear policies that can be adapted to local realities and promoted by champions at all levels is essential. Implementation approaches should be particularly focused on reducing existing health inequities and ensuring new inequities are not introduced.

Anaemia prevention, for example, is not simply a case of providing a prescription for iron tablets. Robust antenatal care, community engagement and education on the importance of dietary diversity, haemoglobin testing, patient medication reminder systems, and task-shifting of iron supplement provision to reach the most at-risk populations in community settings are all essential.[4] Effective implementation requires understanding of and action to address gendered, social, and environmental factors that exacerbate these issues, such as gender norms that influence intrahousehold food allocation (eg, women and girls eating smaller portions than men, or dietary restrictions during menstruation), gendered health access (eg, diminished autonomy or financial control over seeking health care), child marriage and early childbearing, and climate change (eg, rising temperatures increasing infectious disease spread and threatening food security).[41–44]

Heat-stable carbetocin has the advantage of not needing cold-chain transport and refrigerated storage, when compared with oxytocin. However, the unit cost of heat-stable carbetocin might be considered too high in some settings, making its pricing structure an important marketing factor that could scale up its use. Successful and ongoing international efforts are underway to procure heat-stable carbetocin at preferential pricing for low-resource countries with high PPH burden.

Misoprostol might not be as effective as oxytocin or carbetocin for PPH prevention, but it does reduce PPH (≥500 mL), severe PPH (≥1000 mL), and blood transfusion rates, when compared with placebo or no treatment.[3] Misoprostol is heat-stable and affordable, with side-effects that are self-limiting in nature, and so has minimal safety concerns. Misoprostol can therefore be used by community-based health workers to reach women giving birth at home and potentially reduce health disparities. WHO therefore recommends 400 µg oral misoprostol for PPH prevention, which can be administered by community or unskilled health workers if no skilled providers are present at childbirth.[4] An alternative approach is the advanced distribution of misoprostol directly to pregnant women to be self-administered after childbirth, but such an approach should only be considered if targeted monitoring and evaluation are in place.[4]

Research to address medically unindicated caesarean sections is an implementation research priority. Such research should address multiple clinical and non-clinical issues, including financial drivers, at the level of women, providers, facilities, health systems, and national policy. Caesarean births in many countries could soon outnumber vaginal births. Reasons for this increase include health-care provider and institutional financial incentives, health-care providers' fear of litigation, women's fear of vaginal birth, delayed childbearing, and increasing prevalence of comorbidities such as maternal obesity.[45] The consequences of this excess are mostly borne by women—not only in their current pregnancy, but also in future pregnancies.

## Discussion

Prevention of PPH is often seen as synonymous with the prophylactic use of a uterotonic drug after childbirth. However, numerous other steps can help prevent a PPH, including the use of contraception to avoid unwanted pregnancies, addressing modifiable risk factors for PPH,

reducing caesarean sections that are not medically indicated and improving the safety of those that are, and the use of combination uterotonic prophylaxis for women at high risk of PPH. PPH prevention cannot neglect broader public health measures, such as community engagement and birth preparedness, encouraging early and regular antenatal visits, avoiding nutritional deficiencies and anaemia, and addressing obesity and other risk factors. Effective PPH prevention requires a comprehensive approach in addition to the traditional focus on uterotonic prophylaxis at birth.

Evidence supports routine uterotonic prophylaxis for all women. Oxytocin plus misoprostol and oxytocin plus ergometrine are the most effective combinations for preventing PPH of at least 500 mL. However, these combinations are associated with substantial side-effects, and oxytocin plus ergometrine combination can be unsafe because of the risk of hypertension, particularly in those with known hypertensive disease. Therefore, single-agent prophylaxis with oxytocin or carbetocin, or with misoprostol when these are not available or feasible, remains the recommended approach (by WHO, the International Federation of Gynecology and Obstetrics, and the International Confederation of Midwives) for routine use. However, for women at high risk of PPH, combination prophylaxis with oxytocin plus misoprostol can be considered. The recommendation for combination prophylaxis in women at high risk of PPH represents a shift towards risk-stratified prevention strategies. Women with risk factors strongly associated with PPH (eg, anaemia, previous PPH, or caesarean birth), or those with multiple risk factors, could benefit from combination regimens where the potential benefit could outweigh the increased risk of side-effects.

Two modifiable risk factors for PPH demand urgent global attention. First, anaemia, which affects 37% of pregnant women globally, is associated with a 2·4-fold increased risk of PPH and substantially higher mortality rates. Effective interventions, including management of heavy menstrual bleeding, dietary adjustments, treatment of infections, and iron supplementation, are readily available but require systematic implementation.

Caesarean sections that are not medically indicated represent the second modifiable risk factor. The global disparities in caesarean section rates—which exceed 50% in many Latin American countries yet remain below 5% in many sub-Saharan African countries—highlight both overuse and underuse within and between countries. The high PPH risk associated with caesarean birth, combined with an estimated 6·2 million procedures per year that are not medically indicated, represents a substantial and preventable burden. The challenge of placenta accreta spectrum, which is directly linked to increased rates of caesarean sections, exemplifies the cascading consequences of inappropriate intervention. Prevention through judicious use of primary caesarean section is essential. Implementation at scale requires moving beyond clinical guidelines to addressing financial and health system barriers, and the root causes driving women's and providers' preferences for caesarean birth.[46]

Quality assurance of essential medicines remains an important gap. Substandard oxytocin, prevalent in many low-resource settings, undermines prevention efforts and contributes to treatment failures. Strengthening procurement systems and ensuring unbroken supply chains for quality-assured medicines are fundamental requirements for effective implementation. Heat-stable carbetocin eliminates the need for cold-chain maintenance; however, access to the drug is inequitable. Moreover, the affordability and stability of misoprostol make it suitable for community-based births, but at the expense of reduced effectiveness.

Skilled birth attendants have an important role in PPH prevention during and after childbirth. Prevention involves not only the timely use of prophylactic uterotonics, but also managing risk factors (eg, prolonged labour), reducing the risk of PPH related to perineal tearing (by using a hands-on approach to support the perineum during childbirth), avoiding unnecessary episiotomies, identifying and suturing tears early, providing safe and timely caesarean births when indicated, monitoring blood loss and vital signs objectively and frequently after childbirth, and being ready to manage PPH at all times. Where skilled birth attendants are not available, PPH prophylaxis with oral misoprostol and emergency access to appropriately equipped facilities are essential.

Innovations such as heat-stable inhaled, intranasal, or sublingual oxytocin could have a role in PPH prevention in home or community settings that have no access to skilled birth attendants. PPH prevention research priorities include developing improved, cost-effective on-site tests for anaemia diagnosis, and determining optimal dosing regimens for preventive interventions, including the most effective timing of uterotonics relative to cord clamping.

The evidence presented in this Series paper shows that various means for preventing PPH, beyond an exclusive focus on uterotonics, do exist. However, translating evidence into impact requires robust implementation approaches that engage multiple stakeholders, ensure sustained political and financial commitment, and address the broader determinants of maternal health.

#### Contributors

IDG and AC drafted the structure of this Series paper and wrote the first draft. IY and KNS were the main contributors to the Mitigating risk factors for postpartum haemorrhage section. AJD was responsible for the production of figures 1 and 2. All coauthors revised the manuscript at least once, contributed to the literature review, and provided important intellectual input. Authors listed on individual papers within the Series contributed only to those specific papers and not to others. All authors had the opportunity to review each completed paper and agree to the inclusion of the paper they coauthored in this Series.

#### Declaration of interests

IDG and OTO were members of the WHO Steering Group that oversaw the development of the WHO–International Federation of Gynecology

and Obstetrics–International Confederation of Midwives *Consolidated Guidelines for the Prevention, Diagnosis and Treatment of Postpartum Haemorrhage*. ATP was the Chair of the Technical Advisory Group that developed these guidelines. OTO is the Project Coordinator for the Research to Expand Access to Heat-stable Carbetocin for the Treatment of Postpartum Haemorrhage (REACH) trial, which received its main funding support from Unitaid, complementary funding support from MSD for Mothers, in-kind contributions from the Human Reproduction Programme (salary costs), and in-kind donations of heat-stable carbetocin from Ferring Pharmaceuticals for postpartum haemorrhage prophylaxis and as investigational medicinal products to trial-participating sites. All other authors declare no competing interests.

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## Supplementary appendix

This appendix formed part of the original submission and has been peer reviewed. We post it as supplied by the authors.

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# Postpartum haemorrhage: epidemiology, consequences and missed opportunities

# Supplementary Appendix

# 20-May-2026

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**Declaration:**

All Bayesian hierarchical models were performed in R version 4.4.3 and cmdstanr version 2.38.0. Bayesian model code was version-controlled using GitHub for reproducibility.

# Bayesian hierarchical modelling of country-specific, regional and global annual estimates of postpartum haemorrhage (PPH) counts and PPH-related deaths

## 1. Model Overview

Our analysis was conducted to generate country-specific, regional and global annual estimates of PPH counts and PPH-related maternal deaths across 235 countries and territories, as defined by the United Nations Department of Economic and Social Affairs, Population Division (https://population.un.org/wpp/downloads/)[1]. To understand the global, regional and country-specific prevalence of PPH rates (≥500 mL blood loss), we developed a two-stage Bayesian hierarchical modeling framework. In the first stage, we developed a hierarchical model to estimate the PPH rates ≥500 mL following caesarean sections (CS) by leveraging the relationship between PPH (≥500 mL) and severe PPH (≥1000 mL) across delivery modes. In the second stage, we integrated the PPH (≥500 mL) mode of delivery-specific estimates into a PPH burden (PPH counts and PPH-related deaths) estimation model framework that combined country, regional and global PPH incidence and PPH-related deaths. In the PPH burden modeling approach, we incorporated both simple hierarchical structures and ridge regularised regression models. The ridge regularised model included covariates that are predictive of PPH burden at the national, sub-regional and regional level[2]. Detailed notation and description of model specifications are discussed in the corresponding sections (Section 2.1 and 2.2).

## 2. Model Specification and Framework

### 2.1. Stage 1: Caesarean Section PPH ≥ 500mL Estimation Model

While objectively measured vaginal birth (VB) PPH data were available for both PPH ≥500mL and severe PPH ≥1000mL, caesarean section data were limited to only severe PPH (≥1000mL) cases[3]. We therefore developed a Bayesian hierarchical model to estimate the PPH rates for caesarean section by leveraging the relationships between different PPH severity thresholds from multiple sources including meta-analyses[3] and high-quality, low risk of bias randomised controlled trials (RCTs) including the E-MOTIVE[4] and CHAMPION[5] trials.

### 2.1.1. Study Design and Data

A comprehensive literature search was done to identify studies reporting objectively measured PPH prevalence rates stratified by delivery mode. Studies were included if they reported PPH rates using clearly defined thresholds (≥500mL and ≥1000mL) for either vaginal births, caesarean sections, or both delivery modes. Detailed study characteristics were published elsewhere[3]. All included studies employed objective measurement for blood loss estimation with clear PPH threshold definitions. The final dataset for the CS-PPH ≥ 500mL estimation model included 18 studies[4,6-21], the data were transformed as non-negative integer variables[22]. Data extraction included country-level information, study periods, total deliveries stratified by delivery mode, and PPH counts for both PPH (blood loss ≥500mL) and severe (blood loss ≥1000mL) where available[3]. For stability in the CS-PPH ≥ 500mL estimation model, all proportions were bounded away from 0 and 1 using epsilon-adjusted transformations in the data processing.

### 2.1.2. Notation

- N: Total number of studies in the meta-analysis
- s: Study index, s = 1, 2, ..., N
- d: Delivery mode index, $d \in VB, CS$ where VB = vaginal birth, CS = caesarean section
- t: PPH threshold index, $t \in 500,1000$ representing blood loss thresholds in mL
- θ: Vector of all model parameters
- $y_{t,s}$: Observed PPH rate for threshold t in study s
- $n_{t,s}$ : Total number of deliveries for threshold t in study s
- $x_{t,s}$ : Number of PPH cases for threshold t in study s
- $T_s$ : Set of thresholds observed in study s
- $\rho_{\text{E-MOTIVE}}$ : Severity ratio derived from E-MOTIVE trial[4]
- $\rho_{\text{CHAMPION}}$: Severity ratio derived from CHAMPION trial[5]

### 2.1.3. Model Specification

The caesarean section PPH ≥ 500mL model framework assumes that PPH occurs along a continuum of severity with consistent relationships between different threshold definitions, that

are modified by delivery mode-specific factors. This hierarchical structure facilitates the estimation process by incorporating population-level parameters that represent global PPH rates, study-specific random effects that account for methodological differences and population heterogeneity. This framework implemented a weak prior evidence guided by published meta-analysis[3] and clinical trials[4,5], while enabling the propagation of uncertainty throughout the model.

For study s, delivery mode $d \in VB, CS$, and threshold $t \in 500,1000$, the population-specific PPH rate was modelled as:

$$\text{logit}\left(\pi^{d}_{\{t,s\}}\right) = \mu^{d}_{t} + \gamma^{d}_{\{t,s\}} \tag{1}$$

where $\pi^{d}_{\{t,s\}}$ represents the PPH probability for delivery mode d and threshold t in study s; $\mu^{d}_{t}$ represents the baseline log-odds parameter (on logit scale) for delivery mode d and threshold t; and $\gamma^{d}_{\{t,s\}} \sim \text{Normal}(0,\gamma^{d}_{\{t,s\}})$ represents study-specific random effects on the log-odds scale.

The relationship between total PPH (≥500mL) and severe PPH (≥1000mL) was captured through a severity ratio as:

$$\mu_{cs_{total}} = \mu_{cs_{severe}} \times \rho_{severity} \tag{2}$$

where $\rho_{severity}$ represents the population-level severity ratio, modelled through a weak prior framework:

$$\mu_{severity} = \frac{1.2 \times \rho_{\text{E-MOTIVE}} + 1.1 \times \rho_{\text{CHAMPION}} + 1.0 \times \rho_{meta}}{3.3} \qquad \rho_{severity} \sim N\left(\mu_{severity},\ 0.3^{2}\right) \tag{3}$$

Where, $\rho_{meta}$ allowed for observed data estimates. $\mu_{severity}$ and $\rho_{severity}$ were derived from the weighted evidence synthesis in Equation (4), and $\sigma_{severity} = 0.3$ provided moderate uncertainty around the estimate as:

$$\rho_{severity} \sim \text{Normal}\left(\mu_{severity},\ 0.3^2\right) \tag{4}$$

This weighting method accounted for the quality and relevance of evidence sources[4,5], with higher weights assigned to the E-MOTIVE trial due to its low risk of bias. Evidence weighting was based on measurement precision for severity ratio estimation: E-MOTIVE (1.2×) provided standardised blood loss quantification, CHAMPION (1.1×) systematic assessment, and weak prior (1.0×) measurement approaches as shown in equation 3. These trial-based severity ratios served as informative priors while population-based prevalence studies were used for posterior estimates.

### 2.1.4. Priors Specification

We incorporated weak priors for population-level parameters. The pooled estimate of VB-PPH ≥500mL from meta-analysis, E-MOTIVE and CHAMPION trials were 15%, 16.7% and 19.7% respectively. Similarly, the pooled estimate of VB-PPH ≥1000mL from meta-analysis, E-MOTIVE and CHAMPION trials were 4%, 4.2% and 4.3% respectively. Therefore, priors were defined for vaginal and caesarean births across two severity thresholds:

Vaginal birth total PPH (≥500mL):

$$\mu^{VB}_{500,\text{logit}} \sim \text{Normal}(\text{logit}(0.15), 0.04 \times 0.7)$$

Where logit(0.15) ≈ -1.735 represents the prior mean on the log-odds scale corresponding to 15% PPH rate, with prior standard deviation of 0.06 providing moderate uncertainty with weak prior and high quality RCT estimates[3,4].

Vaginal birth severe PPH (≥1000mL):

$$\mu^{VB}_{1000} \sim \text{Normal}(\text{logit}(0.04), 0.015 \times 0.7)$$

Where logit(0.04) ≈ -3.178 represents the prior mean on the log-odds scale corresponding to 4% severe PPH rate.

Caesarean section severe PPH (≥1000mL):

$$\mu_{1000}^{CS} \sim \text{Normal}(\text{logit}(0.08), 0.025 \times 0.7)$$

Where logit (0.08) ≈ -2.440 represents the prior mean on the log-odds scale corresponding to 8% caesarean section severe PPH rate. The scaling factor of 0.7 was applied to prior standard deviations to account for substantial learning from observed data[23]. The purpose of using a scaling factor was to ensure the prior is dominated by the likelihood (posterior SD << prior SD) while avoiding numerical instability near the parameter boundaries[23].

### 2.1.5. Likelihood Specification

The observed PPH rates were modelled using beta distributions to accommodate overdispersion relative to binomial sampling as,

$$y_{t,s} \sim \text{Beta!}\left(\alpha_{t,s}, \beta_{t,s}\right) \tag{5}$$

Where, the parameters were defined as $\alpha_{t,s} = \max\left(0.5,\ \pi_{t,s}\varphi_t\right)$, $\beta_{t,s} = \max\left(0.5,\ \left(1-\pi_{t,s}\right)\varphi_t\right)$ and $\pi_{t,s}$denotes the event probability for outcome t in study s. The parameter $\varphi_t$ represents the precision (overdispersion) parameter, which controls the concentration of the beta distribution. A lower bound of 0.5 was imposed on both $\alpha_{t,s}$and $\beta_{t,s}$to prevent numerical instabilities when event probabilities approach 0 or 1 and to ensure identifiability of the likelihood. The precision parameters $\varphi_t$for each outcome were assigned outcome-specific gamma priors[24]: $\varphi_{VB,total} \sim \Gamma(8,0.05)$, $\varphi_{VB,severe} \sim \Gamma(10,0.055)$, $\varphi_{CS,severe} \sim \Gamma(12,0.06)$ was chosen to provide weakly informative regularisation while maintaining numerical stability of the hierarchical model.

All hierarchical models were specified and compiled in cmdstanr, a probabilistic programming interface optimised for Bayesian inference, and fitted via Markov chain Monte Carlo (MCMC) sampling[23-26]. Model execution, diagnostics, and post-processing were conducted in the R statistical environment using the posterior packages[26]. We employed four parallel chains, each

with 2,500 iterations (1,000 warmup, 1,500 posterior samples), yielding 6,000 posterior samples for inference. To improve sampling efficiency and reduce correlations between hierarchical parameters, we employed non-centred parameterisation for study-level effects:

$$\gamma^{d}_{t,s} = \sigma^{d}_{t,study} \times \varepsilon^{d}_{t,s} \quad (6)$$

Where, $\gamma^{d}_{t,s}$ represents the study-specific deviation for delivery mode d and threshold t in study s; $\sigma^{d}_{t,study}$ represents the between-study standard deviation parameter, and $\varepsilon^{d}_{t,s}$ ~ Normal (0, 1) represents standardised study effects.

### 2.1.6. Model Validation and Sensitivity Analysis

We evaluated convergence diagnostics for model performance through multiple metrics including, Gelman–Rubin statistics, R-hat ($\widehat{R}$), effective sample sizes (ESS) which exceeded 200 for key parameters, and inspection of MCMC trace plots showing adequate chain mixing (Figure S1).

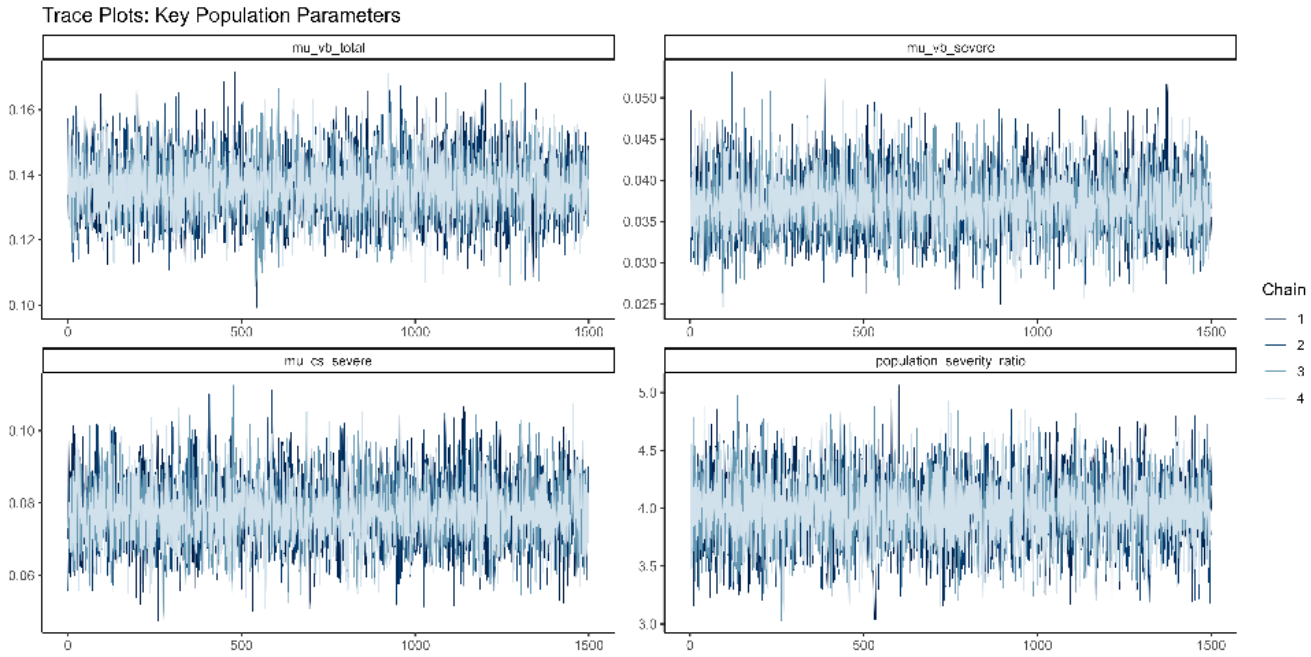


Figure S1. Trace plots for key posterior parameters in the Bayesian hierarchical model assessing CS-PPH rates. Each panel displays the MCMC trace across four sampling chains for one model parameter: vaginal birth total PPH rate (mu_vb_total,

$\mu_{500}^{VB}$), vaginal birth severe PPH rate (mu_vb_severe, $\mu_{1000}^{VB}$), caesarean section severe PPH rate (mu_cs_severe, $\mu_{1000}^{CS}$), and the population-level severity risk ratio (population_severity_ratio, $\rho_{severity}$).

To assess the model adequacy in reproducing observed data patterns, we performed a series of posterior predictive checks (PPCs). For the PPCs, we generated replicated datasets (y_rep) by simulating the posterior predictive distribution of each model. For each outcome of interest, PPH rates disaggregated by delivery mode, we computed a set of discrepancy measures to capture both central tendency and variability. These included: sample mean, representing the expected central value of the distribution; standard deviation, capturing the spread of the distribution and reflecting the degree of heterogeneity across countries; and maximum value, indicating the extreme tail behaviour and ensuring the model did not underestimate the burden in high-prevalence countries (Figure S2).

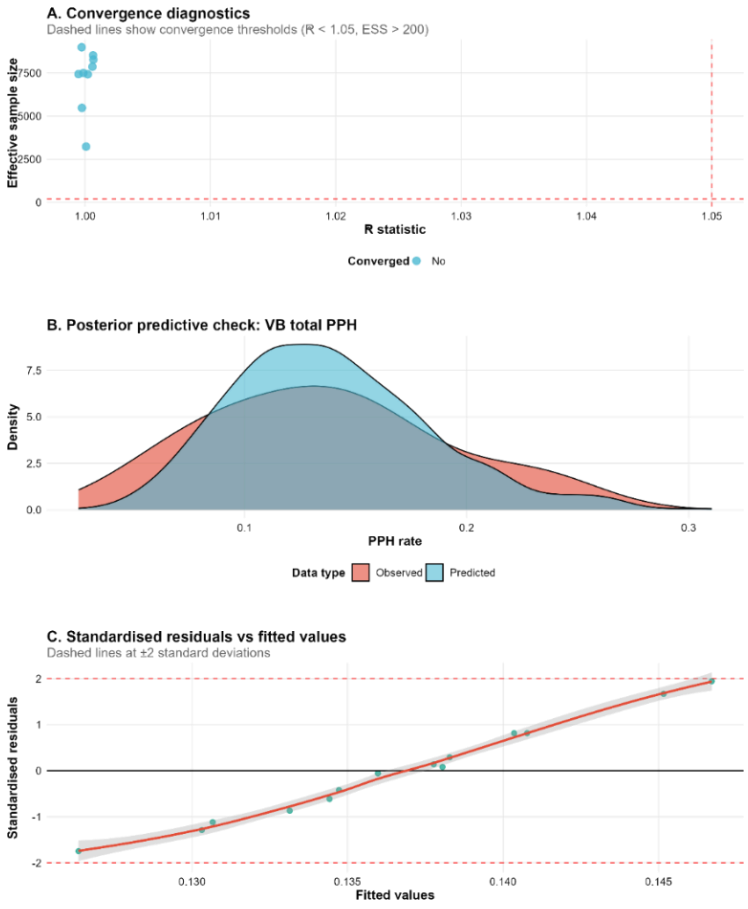


Figure S2. Model Validation Diagnostics for Bayesian Estimation of CS-PPH rates. Panel (A) shows the convergence diagnostics where each point represents a study-level parameter, plotted by its $\hat{R}$ (x-axis) and effective sample size (y-axis). All parameters

had $\widehat{R}$ values <1.05 and ESS > 500, indicating strong MCMC convergence. Panel (B) illustrates posterior predictive check: Overlay of observed (red) and posterior predictive (blue) distributions for vaginal birth (VB) postpartum haemorrhage (PPH) rates. The alignment between observed and simulated data suggests the model accurately captures key features of the observed distribution. Panel (C) shows the standardised residuals versus fitted values: Residuals are symmetrically distributed around zero, with most falling within ±2 standard deviations (dashed lines), supporting model adequacy and absence of systematic bias.

Further, we compared prior distributions with posterior estimates obtained through MCMC sampling to examine the extent of prior influence and model learning. Overlap between prior and posterior distributions showed consistency between prior knowledge and observed data. Our model parameters showing posterior shifts relative to priors suggested study-level data provided meaningful updates to prior beliefs as shown in Figure S3.

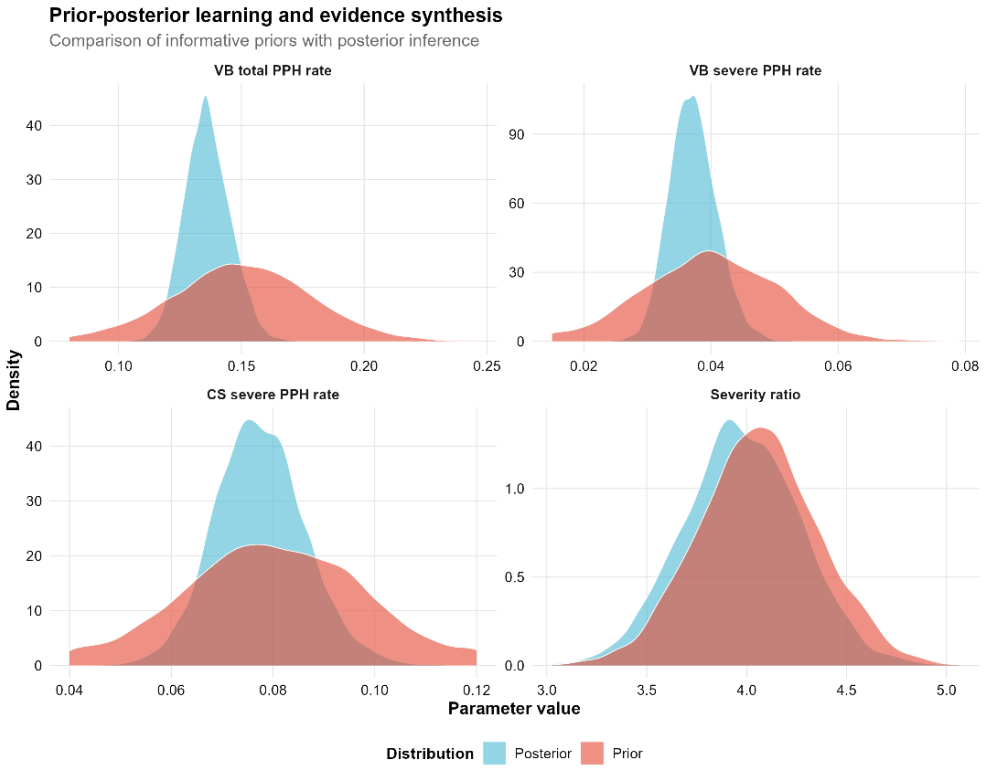


Figure S3. Prior- posterior comparison for model parameters. This figure shows the prior (red) and posterior (blue) distributions for four key parameters in the Bayesian hierarchical model: Panel (A) Postpartum haemorrhage (PPH) rate following vaginal birth (VB), Panel (B) Severe PPH rate following VB, Panel (C) Severe PPH rate following caesarean section (CS) and Panel (D) Study-level severity risk ratio (CS:VB). Posterior distributions were derived from the fitted model using MCMC sampling. Informative priors were obtained from a synthesis of meta-analyses and individual trial estimates (E-MOTIVE and CHAMPION) for sensitivity analysis.

Predictive performance of the model was assessed using root mean squared error (RMSE) and the mean absolute error (MAE) between observed outcomes and posterior predictive medians (Table S1). Also, uncertainty calibration was examined using coverage probabilities, defined as the proportion of observed outcomes lying within the central 95% posterior credible interval[23,27].

Finally, we observed that caesarean section was associated with increased rates of PPH, that the estimated rate following caesarean section PPH ≥500 mL was 30.9% (95% credible interval: 24.9%- 37.6%), compared to 12.6% (95% confidence interval: 10.1% -15.2%)[3] for vaginal birth. The corresponding posterior risk ratios (RRs) indicated more than twofold increase in risk for caesarean section: RR =2.27 (95% credible interval: 1.66- 3.01) (Figure S4).

**Table S1: Caesarean Section PPH ≥ 500mL Estimation Model Performance**

| Parameter | RMSE | MAE | Coverage (95%) | PPC p-value (mean) | PPC p-value (sd) |
|---|---|---|---|---|---|
| VB total PPH | 0.047 | 0.038 | 0.929 | 0.496 | 0.12 |
| VB severe PPH | 0.017 | 0.015 | 0.889 | 0.439 | 0.39 |
| CS severe PPH | 0.033 | 0.029 | 1 | 0.406 | 0.05 |

Model Performance: Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were calculated for posterior predictive means versus observed values. The combination of error metrics (RMSE, MAE), interval calibration (coverage), and distributional checks (PPC p-values) was chosen to provide a comprehensive assessment of predictive accuracy, uncertainty validity, and model fit across central tendencies and higher-order moments. The CS-PPH estimation model showed a moderate predictive accuracy across all PPH parameters, with RMSE values ranging from 0.017 to 0.047 and MAE values from 0.015 to 0.038. For the coverage probability, VB severe PPH showed under coverage due to moderate capture of uncertainty in VB-PPH ≥1000 mL parameter, possibly due to heterogeneity between the studies[3]. The mean centred posterior predictive probability p-values were close to 0.5 across all parameters (0.406-0.496), suggesting adequate capture of central tendencies.

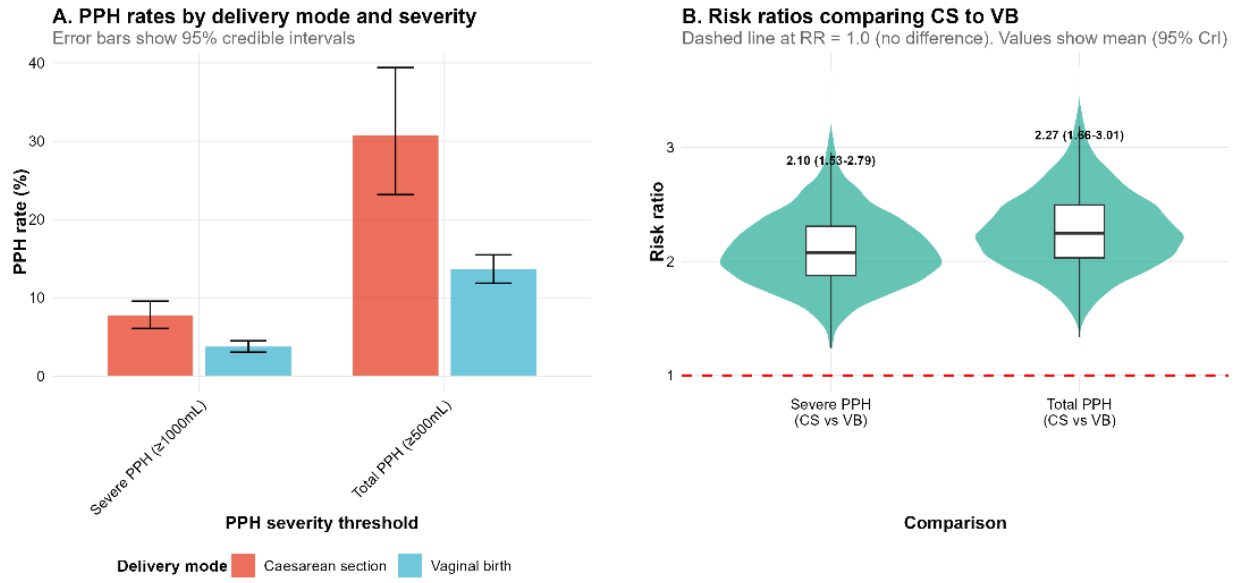


Figure S4. Estimated PPH rates and relative risk by mode of delivery. Panel A represents the posterior mean estimates of PPH rates following caesarean section (red) and vaginal birth (blue), stratified by severity thresholds: ≥1000 mL (severe PPH) and ≥500 mL (PPH). Error bars denote 95% credible intervals (CrI). Panel B shows the posterior distributions of risk ratios (RRs) comparing PPH rates for caesarean section versus vaginal birth, with 95% credible intervals. The dashed red line indicates the null value (RR = 1). Caesarean section was associated with a more than two-fold increased risk of both severe PPH (RR = 2.10, 95% CrI: 1.53–2.79) and PPH (RR = 2.27, 95% CrI: 1.66–3.01).

### 2.1.7. R codes for Stage 1 Model for CS-PPH ≥500 mL estimation

```
// Prior
mu_vb_total  ~ normal(0.15, 0.028);   // Normal(0.15, 0.04 × 0.7)
mu_vb_severe ~ normal(0.04, 0.0105);  // Normal(0.04, 0.015 × 0.7)
mu_cs_severe ~ normal(0.08, 0.0175);  // Normal(0.08, 0.025 × 0.7)
// Severity ratio: weak meta-prior updated by E-MOTIVE and CHAMPION
meta_severity_ratio      ~ normal(4.0, 1.0);
real weighted_ratio = (1.2 * emotive_severity_ratio +
                       1.1 * champion_severity_ratio +
                       1.0 * meta_severity_ratio) / 3.3;

population_severity_ratio ~ normal(weighted_ratio, 0.3)
// Liklihood
```

```
for (s in 1:N_studies) {
  if (has_vb_total[s] == 1) {
    real alpha = fmax(0.5, study_vb_total[s] * phi_vb_total);
    real beta  = fmax(0.5, (1 - study_vb_total[s]) * phi_vb_total);
    target += beta_lpdf(vb_total_rates[s] | alpha, beta);
  }
  if (has_vb_severe[s] == 1) {
    real alpha = fmax(0.5, study_vb_severe[s] * phi_vb_severe);
    real beta  = fmax(0.5, (1 - study_vb_severe[s]) * phi_vb_severe);
    target += beta_lpdf(vb_severe_rates[s] | alpha, beta);
  }
  if (has_cs_severe[s] == 1) {
    real alpha = fmax(0.5, study_cs_severe[s] * phi_cs_severe);
    real beta  = fmax(0.5, (1 - study_cs_severe[s]) * phi_cs_severe);
    target += beta_lpdf(cs_severe_rates[s] | alpha, beta);
  }
}
```

**2.2. Stage 2: PPH Burden (Counts and Deaths) Model**

The country and region- specific PPH burden (including PPH counts and PPH-related deaths) estimation framework was constructed using two hierarchical structures. This was done to capture heterogeneity in sub-regional caesarean section rates[28] and regional PPH mortality patterns[29]. The sub-regional hierarchy captured caesarean section rates across fifteen UN sub-regions, accounting for geographic variations in CS rates, i.e., ranging from approximately 6% in parts of Sub-Saharan Africa to over 50% in parts of Latin America and Eastern Asia[28]. The SDG regional hierarchy accounted for PPH mortality patterns through eight SDG regions, that showed heterogeneity in emergency obstetric care across different settings[30,31]. We also constrained the hierarchical model for CS rates and PPH death fractions using the uncertainty bounds from the corresponding studies[28,29]. Our hierarchical framework captured the case-fatality rate variations across the SDG regions, with regions such as Sub-Saharan Africa showing higher mortality risks

due to limited access to life-saving interventions[29,31]. The modelling framework adopted a three-level hierarchical structure as follows,

- Global level: Baseline parameters representing PPH risks and deaths across all countries.
- Regional level: Random effects capturing deviations for eight SDG regions. These reflect major differences in health system readiness, obstetric practices, and mortality risk.
- Country level: Random effects for individual countries, capturing residual heterogeneity due to local health system capacity, clinical management, and unmeasured factors.

The PPH burden model framework adopt partial pooling, where countries with limited data were informed by regional and global patterns, while countries with better data retained influence within their region. This balance avoids overfitting to sparse national data while maintaining sufficient flexibility to capture genuine heterogeneity.

### 2.2.1. Study Design and Data

We obtained annual live birth estimates for all UN member states and territories (n=235) from the United Nations World Population Prospects 2024, which synthesises data from censuses, nationally representative surveys, and vital registration systems (World Population Prospects) to project birth estimates[1]. Maternal deaths were taken from the Maternal Mortality Estimation Inter-Agency Group (MMEIG), which applies a Bayesian model (BMat) to harmonise survey and vital registration sources (Maternal mortality ratio (per 100 000 live births))[32]. UN-sub-region-specific caesarean section rates were extracted from CS rate projections published by Betran et al., which draw on Demographic and Health Surveys (DHS), Multiple Indicator Cluster Surveys (MICS), and administrative data[28]. For covariate analyses, we used indicators of health system and socioeconomic capacity: gross domestic product (GDP) per capita (World Bank World Development Indicators), antenatal care coverage (≥4 visits; WHO/UNICEF), and skilled birth attendance coverage (WHO/UNICEF)[33-35]. Detailed data sources and data processing are explained in the following sections.

We conducted a literature search in Google and MEDLINE (via PubMed) from inception to June 2025 and using terms for postpartum haemorrhage, maternal mortality, and mode of delivery, and national confidential enquiry reports[36,37]. Eligible national and/or population level reports on maternal deaths due to PPH that were stratified by delivery mode (vaginal birth versus caesarean

section) were included in the meta-analysis. Case reports and datasets lacking a clear definition of PPH were excluded. Data on PPH cases and deaths by mode of delivery were extracted and synthesised in a random-effects meta-analysis to estimate the odds ratio of PPH mortality comparing caesarean with vaginal birth. This informed the prior distribution in our PPH burden Bayesian model (Table S2).

**Table S2: Meta-Analysis of postpartum haemorrhage (PPH)- related maternal deaths by delivery mode**

| Author | Country | Study Description/Population | CS-PPH Deaths | Total CS Births | VB-PPH Deaths | Total VB Births | Odds ratio (95% CI) | Risk of Bias |
|---|---|---|---|---|---|---|---|---|
| Esteves-Pereira et al., [38] | Brazil | Population-based case-control in eight states (73 postpartum maternal deaths, 9,221 controls from the Birth in Brazil survey) | 26 | 4,303 | 14 | 4,843 | 2.1 (1.09-4.02) | Moderate- Study excluded private facilities and high-risk pregnancies; not fully representative nationally |
| Deneux-Tharaux et al, [39] | France | Population-based case-control study (level of evidence II-2). Cases were identified from the national Confidential Enquiry on Maternal Deaths; controls were drawn from the 1998 French National Perinatal Survey | 6 | 1,550 | 19 | 8,711 | 1.78 (0.71-4.46) | Moderate–high: National coverage but dated (1990s); may not reflect current practice |
| Confidential enquiry [40] | Malaysia | National confidential enquiry (surveillance and audit) of all maternal deaths. All reported maternal deaths in Malaysia between 2009-2011 | 5 | 117,526 | 10 | 368,010 | 1.57 (0.54-4.58) | Low: National coverage, high-quality confidential enquiry |
| Confidential enquiry [36] | South Africa | National confidential enquiry into maternal deaths. All maternal deaths in South Africa in 2023, captured through the Maternal Morbidity and | 41 | 284,459 | 49 | 598,785 | 1.76 (1.16-2.67) | Low: Comprehensive national system, included public and private facilities |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mortality Audit System (MaMMAS) with cross-checking against the District Health Information System (DHIS) | | | | | | |
| Kamilya et al., [41] | India | Retrospective cohort study from a single centre. (High risk of bias was assessed) | 9 | 13,627 | 12 | 30,215 | 1.66 (0.7-3.95) | High: Single-centre referral hospital; excluded comorbidities; not nationally representative |
| Riches et al., [42] | Malawi | Retrospective national surveillance analysis (2020–2022) using the Malawi MATSurvey digital maternal death surveillance system | 48 | 89,098 | 93 | 465,375 | 2.7 (1.9-3.82) | Moderate: Most facility coverage, but may miss community births outside formal health system |
| Adebayo et al., [43] | Nigeria | Cross-sectional secondary data analysis of the Maternal and Perinatal Database for Quality, Equity and Dignity (MPD-4-QED). Multicentre nationwide referral-hospital study, with stratified analysis by mode of delivery | 56 | 28,843 | 48 | 45,911 | 1.86 (1.26-2.73) | High: Only referral-level, excluded majority of deliveries (community and lower-level facilities) |

Studies included in meta-analysis of PPH-related deaths in caesarean section. We searched PUBMED, Google Scholar, Government reports and confidential enquiries and screened the articles for studies and/or reports that assessed PPH-related deaths in vaginal and caesarean births. Two authors (N.P and S.K.N) independently screened and assessed the articles. Data were drawn from population studies, confidential enquiries and surveillance reports [36,38-43] independently by two authors (N.P and S.K.N).

Caesarean section postpartum haemorrhage (CS-PPH) deaths and vaginal birth postpartum haemorrhage (VB-PPH) deaths refer to maternal deaths due to PPH following caesarean and vaginal deliveries, respectively.

Total CS and VB deliveries represent the denominators used to estimate the odds ratios.

Confidence intervals (95% CI) show the uncertainty around the point estimates.

Risk of bias of included studies were assessed by Newcastle-Ottawa Scale (NOS)[44]

For each study, we extracted the number of maternal deaths due to PPH following CS and VB, along with the corresponding denominators of deliveries by mode. These data were organised into two-by-two tables of deaths and survivors by mode of delivery. Odds ratios comparing the risk of PPH death after CS versus VB were then calculated from these tables, with 95% confidence intervals derived using standard inverse-variance methods. Where necessary, small-sample corrections were applied to avoid unstable estimates. This approach was used due to the heterogeneous study designs, while allowing the estimates to be pooled in the random-effects meta-analysis.

### 2.2.2. Notation

- c: Country index, c = 1, 2, ..., C where C = 235 (UN member states and territories)
- r: SDG region index, r = 1, 2, ..., 8 (eight SDG regions)
- s: UN sub-region index, s = 1, 2, ..., 15 (fifteen UN sub-regions)
- t: Time index (year), t = 2000, 2001, ..., 2030
- d: Delivery mode index, $d \in VB, CS$ where VB = vaginal birth, CS = caesarean section
- k: Covariate index, k = 1, 2, ..., K where K = 3 (number of covariates)
- r[c]: SDG region containing country c
- s[c]: UN sub-region containing country c
- $\mu_{global}^{VB}$: Global baseline log-odds for vaginal birth PPH ≥500mL
- $\mu_{global}^{CS}$: Global baseline log-odds for caesarean section PPH ≥500mL
- $\alpha_{r[c]}^{d}$: SDG regional random effect for delivery mode d in region r[c]
- $\beta_{c}^{d}$: Country-specific random effect for delivery mode d in country c
- $\varepsilon_{c,t}^{d}$: Residual random effect for delivery mode d, country c, time t
- $\sigma_{region}^{d}$: Between-region standard deviation for delivery mode d
- $\sigma_{country}^{d}$: Between-country standard deviation for delivery mode d
- $\sigma_{residual}^{d}$: Residual standard deviation for delivery mode d
- $\gamma_{k}^{d}$: Effect coefficient for covariate k and delivery mode d
- $\lambda$: Ridge regularisation parameter ($\lambda = 5.0$)
- $\text{Scale}_{cov}$: Covariate scaling factor (0.1)

- $B_{c,t}$ : Total births in country c at time t
- $B_{c,t}^{VB}$ : Vaginal births in country c at time t
- $B_{c,t}^{CS}$ : Caesarean births in country c at time t
- $M_{c,t}$: Total maternal deaths in country c at time t (from MMEIG)
- $D_{c,t}^{PPH}$: Total PPH deaths in country c at time t
- $D_{c,t}^{VB}$: VB-attributable PPH deaths in country c at time t
- $D_{c,t}^{CS}$: CS-attributable PPH deaths in country c at time t
- $N_{c,t}^{VB}$: VB-PPH cases in country c at time t
- $N_{c,t}^{CS}$: CS-PPH cases in country c at time t
- $\psi_r$: PPH death fraction for SDG region r
- $\rho_{s[c],t}^{CS}$: Caesarean section delivery rate for sub-region s[c] at time t
- $OR_{CS:VB}^{PPH}$: Odds ratio for PPH case-fatality, CS versus VB
- $\alpha_{global}^{deaths}$: Global intercept for the log-linear maternal death model
- $\alpha_{r[c]}^{deaths}$: Regional random effect for the log-linear maternal death model
- $\sigma_{deaths}$: Observation noise in the log-linear death model
- $\widehat{R}$: Gelman–Rubin convergence statistic

### 2.2.3. Prior Specification

Priors for global PPH rates, $\pi_{global}^{VB}$ were obtained from the pooled estimate 12.6% (95% confidence interval: 10.1% -15.2%) of a meta-analysis[3]. The prior for $\pi_{global}^{CS}$ were derived from the Stage 1 CS-PPH ≥ 500mL Bayesian estimation model at mean CS-PPH ≥ 500mL of 30.9% (95% credible interval: 24.9%- 37.6%). These were specified on the logit scale to ensure probabilities remain bounded between 0 and 1. For vaginal birth PPH ≥500 mL,

$$\text{logit}\left(\pi_{global}^{VB}\right) \sim \text{Normal}(-1.936,\ 0.122^2)$$

corresponding to 12.6% prevalence with logit standard error of 0.119 )[3] and for caesarean section PPH ≥500 mL,

$$\text{logit}\left(\pi_{global}^{CS}\right) \sim \text{Normal}(-0.802,\ 0.153^2)$$

corresponding to 30.9% prevalence with logit standard error of 0.152 and were implemented in the PPH burden model framework. The PPH count estimation framework at country-level integrated delivery mode distribution with delivery-specific PPH risks. For each country c in year t, total PPH cases were calculated as the weighted sum of vaginal birth and caesarean section contributions:

$$\mathrm{TotalPPHCases}_{c,t} = \left(\mathrm{VBBirths}_{c,t} \times \pi^{VB}_{500,c,t}\right) + \left(\mathrm{CSBirths}_{c,t} \times \pi^{CS}_{500,c,t}\right) \quad (7)$$

where: $\mathrm{VBBirths}_{c,t}$ = number of vaginal births in country c at time t; $\mathrm{CSBirths}_{c,t}$ = number of caesarean births in country c at time t; $\pi^{VB}_{500,c,t}$= country-specific vaginal birth PPH rate (≥500mL), and $\pi^{CS}_{500,c,t}$= country-specific caesarean section PPH rate (≥500mL).

Birth distribution follows subregional caesarean rates derived from Betran et al.'s projections[28], where:

$$\mathrm{VBBirths}_c, t = \mathrm{TotalBirths}_c, t \times (1 - \mathrm{CSRate}_s[c], t)$$

$$\mathrm{CSBirths}_c, t = \mathrm{TotalBirths}_c, t \times \mathrm{CSRate}_s[c], t$$

where s[c] denotes the subregion containing country c, and $\mathrm{CSRate}_s[c], t$ represents the caesarean section rate for that subregion at time t. Total birth numbers were obtained from UN World Population Prospects, providing the denominator for calculating PPH rates and establishing the baseline population at risk for burden calculation[1]. The country-specific PPH rates incorporated hierarchical random effects as:

$$\mathrm{logit}(\pi^{VB}500, c, t) = \mu^{VB}\mathrm{global} + \alpha^{VB}r[c] + \beta^{VB}c + Xc, t\gamma^{VB} + \varepsilon^{VB}c, t \quad (7a)$$

$$\mathrm{logit}(\pi^{CS}500, c, t) = \mu^{CS}\mathrm{global} + \alpha^{CS}r[c] + \beta^{CS}c + Xc, t\gamma^{CS} + \varepsilon^{CS}c, t \quad (7b)$$

where $\mu^{VB}global$ represents the global baseline log-odds from Stage 1; $\alpha^{VB}r[c] \sim Normal\left(0,\ \sigma^{d}_{region}\right)$ captures SDG regional random effects; $\beta^{VB}c \sim Normal\left(0, \sigma^{d}_{country}\right)$ represents country-specific random effects; $X_{c,t}\gamma^{d}$ denotes covariate effects; and $\varepsilon^{CS}c,t \sim Normal\left(0, \sigma^{d}_{residual}\right)$ represents residual variation.

The regional-level PPH death fractions derived from Cresswell et al.'s multi-country survey data[29], were modeled as,

$$\psi_r \sim N\left(\mu_r^{\psi},\ \left(\sigma_r^{\psi}\right)^2\right) \tag{8}$$

Where, $\psi_r$ = PPH death fraction for SDG region r and$\mu_r^{\psi}$ represents the regional point estimate of the PPH death fraction derived from Cresswell et al.,[29] and $\sigma_r^{\psi}$ represents the corresponding regional standard deviation. To allocate PPH deaths between delivery modes, we used a weighted proportional allocation method in which each delivery mode's share of total PPH deaths was determined by its share of PPH cases, scaled by the estimated odds ratio for PPH case-fatality between CS and VB deliveries $\left(OR^{PPH}_{CS:VB} = 2.18\right)$. The allocation method used weighted proportional allocation as:

$$D^{VB}_{c,t} = D^{PPH}_{c,t} \times \frac{N^{VB}_{c,t} \cdot w^{VB}}{\left(N^{VB}_{c,t} \cdot w^{VB}\right) + \left(N^{CS}_{c,t} \cdot w^{CS}\right)} \tag{9a}$$

$$D^{CS}_{c,t} = D^{PPH}_{c,t} \times \frac{N^{CS}_{c,t} \cdot w^{CS}}{\left(N^{VB}_{c,t} \cdot w^{VB}\right) + \left(N^{CS}_{c,t} \cdot w^{CS}\right)} \tag{9b}$$

where:

Total PPH deaths were estimated by $D_{c,t}^{VB} + D_{c,t}^{CS} = D_{c,t}^{PPH}$; $w^{VB}$, $w^{CS}$ = Death weighting factors for vaginal birth and caesarean section PPH respectively. The ratio $w^{CS}/w^{VB}$ equals the odds ratio for PPH case-fatality comparing caesarean sections to vaginal delivery.

The caesarean section PPH -related deaths ratio compared to PPH-related deaths following vaginal births were derived from meta-analysis of seven reports (Table S2) including maternal mortality confidential inquiries and population-level surveillance studies[36,38-43]. All these reports have shown delivery mode-specific PPH-related death data with adequate sample sizes and rigorous case classification procedures[36,38-43]. The caesarean section PPH death weight estimation was modeled as:

$$\log\left(OR_{CS:VB}^{PPH}\right) \sim \text{Normal}(0.779, 0.086^2) \tag{10}$$

This prior specification corresponds to the pooled estimate of meta-analysis of studies reporting maternal PPH-related deaths in vaginal and caesarean sections, OR = 2.18 (95% confidence interval: 1.84- 2.58). It showed that women experiencing PPH following caesarean delivery have approximately 2.18 times the odds of death compared to those with PPH following vaginal delivery. The weighting factors were set as:

$$w_{VB} = 1.0 \text{ (reference category)}$$

$$w_{CS} = \exp\left(\log\left(OR_{CS:VB}^{PPH}\right)\right) = OR_{CS:VB}^{PPH} \tag{11}$$

The log-normal specification ensures positive odds ratios while providing symmetric uncertainty on the log scale. The hierarchical variance components employed exponential priors to ensure positive values while maintaining computational tractability and providing moderate regularisation:

$$\sigma_{country}^{VB}, \sigma_{country}^{CS} \sim \text{Exponential}(1.5)$$

And,

$$\sigma^{VB}_{country}, \sigma^{CS}_{country} \sim \text{Exponential}(2.0)$$

And,

$$\sigma_{deaths} \sim \text{Exponential}(1.0)$$

The exponential prior specifications offered moderate regularisation while allowing substantial heterogeneity when supported by the data.

### 2.2.4. Model Specification

We developed two independent Bayesian hierarchical models to estimate country-specific, regional and global PPH counts and deaths, incorporating covariates. We developed these two models in an increasing level of complexity and regularisation to balance model flexibility with overfitting prevention. First, a baseline three-level hierarchical Bayesian model was developed to capture variation in PPH risk across global, regional, and country levels while borrowing information across the hierarchy. This model showed the foundation for subsequent extensions and allows estimation in settings where country-level data are sparse or absent. For country c in region r and delivery mode $d \in VB, CS$, the baseline hierarchical model was specified as:

$$\text{logit}(\pi^d_c) = \mu^d_{global} + \alpha^d_r + \beta^d_c \quad (12)$$

where $\mu^d_{global}$ represents the global baseline log-odds derived from meta-analytical evidence; $\alpha^d_r \sim \text{Normal}(0, \sigma^d_{region})$ captures systematic differences between SDG regions; and $\beta^d_c \sim \text{Normal}(0, \sigma^d_{country})$ reflects local heterogeneity not explained by regional patterns.

Following the baseline hierarchical model, we developed a ridge regularised model (Figure S5) by incorporating socioeconomic and health system covariates including GDP per capita, skilled birth attendance coverage (SBA), and antenatal care coverage (ANC). These indicators were selected due to their associations with maternal health outcomes and can be accessed via World Health Organization (WHO) data portal for Indicators[45]. We added these indicators as standardised covariates using z-score transformation as predictive covariates in the ridge

regularised model. Proportion-based covariates, SBA[34] and ANC[35] were logit-transformed prior to standardization to address boundary constraints and improve posterior sampling as:

$$X_{transformed} = \text{logit}(\text{proportion})$$

$$[X_{standardised} = \frac{X_{transformed} - \overline{X_{transformed}}}{SD(X_{transformed})}]$$

We used Gaussian priors with variance scaled by a hyperparameter λ, controlling the degree of shrinkage for the covariate coefficients[23]. Mainly, we implemented ridge regularisation to execute uniform shrinkage across all coefficients, reducing overfitting and improving generalizability to out-of-sample countries and time periods (Figure S3). For country c in region r and delivery mode d, the ridge-covariate model was specified as,

$$\text{logit}(\pi_c^d) = \mu_{global}^d + \alpha_r^d + \beta_c^d + 0.1 \times \Sigma_k(X_c, k \times \gamma_k^d) \quad (13)$$

where:

- $X_c, k$ : Standardized covariate k for country c
- $\gamma_k^d$: Covariate-specific effect coefficient for delivery mode d and covariate k
- 0.1: Conservative scaling factor applied to stabilize estimation and prevent excessive influence of covariate effects on the hierarchical structure

Ridge priors were assigned to all covariate coefficients:

$$\gamma_k^d \sim \text{Normal}\left(0, \left(1/\sqrt{\lambda}\right)^2\right), \text{where } \lambda = 5.0 \quad (14)$$

This prior specification corresponds to an L2 penalty with a standard deviation of $1/\sqrt{5} \approx 0.447$. We used a ridge penalty, that was controlled by a tuning parameter, λ. To identify a plausible value for λ, we carried out a sensitivity analysis in which we tested a wide range of possible

strengths of this penalty. For each value, we re-fitted the full model and assessed how well it predicted countries not used during model fitting, using leave-one-out cross-validation (LOO)[2]. On this basis, the ridge regularisation parameter $\lambda = 5.0$ was selected which provided stable model behaviour, good convergence of the Markov chains, and covariate effects that remained small.

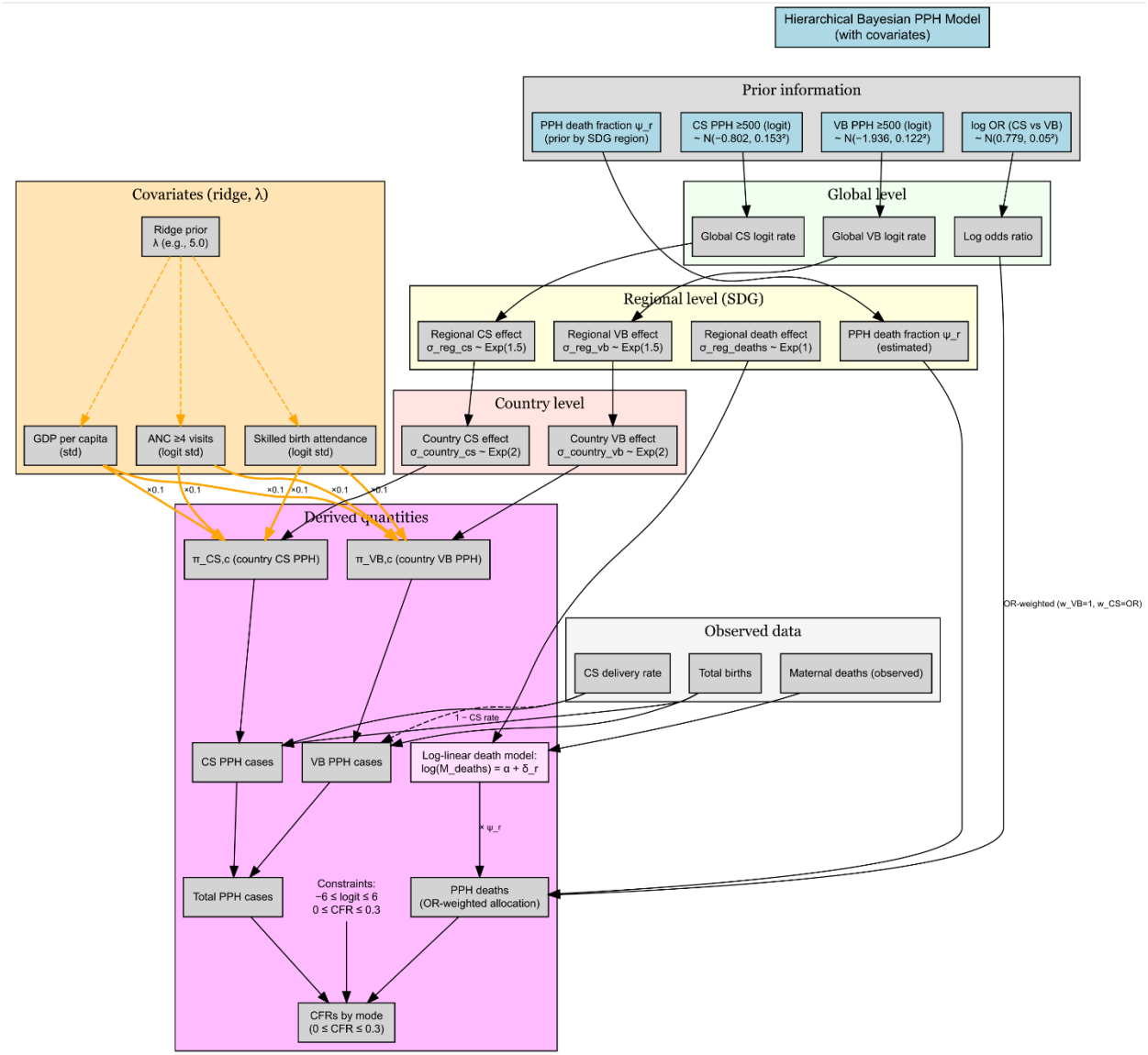


Figure S5. Hierarchical Bayesian ridge-regularised model framework for postpartum haemorrhage (PPH) mortality estimation.

This directed acyclic graph illustrates the information flow and statistical dependencies in the ridge-regularised hierarchical Bayesian model. The framework incorporates three nested levels of variation (global, regional, country) and applies L2 penalty regularisation to covariate effects. Blue (Priors): PPH rate priors for vaginal birth (VB) from meta-analysis and caesarean section (CS) from Stage 1 model estimates; the odds ratio prior constrains relative PPH mortality risk between CS and VB. Green (Global parameters): Baseline log-odds of PPH risk and mortality relationships across all countries. Yellow (Regional effects): Sustainable Development Goal (SDG) region–specific deviations from global baselines, capturing systematic differences in PPH burden (e.g., Cresswell et al.'s regional mortality analysis[29]). Orange (Covariates): Ridge-regularised effects ($\lambda = 5.0$) for GDP per capita, antenatal care (ANC) coverage, and skilled birth attendance (SBA) coverage. Purple (Country effects): Country-specific random effects accounting for residual variation unexplained by regional patterns or covariates. Grey (Observed data): Inputs including total births, CS delivery rates, maternal deaths, and covariates. Pink (Generated quantities): Model outputs including estimated PPH cases by delivery mode, deaths allocated by odds ratio, and case fatality rates (CFRs). Arrows represent statistical dependencies and flow of information: priors to parameters (blue), global to regional (green), regional to country (orange), covariate effects on country estimates (red/orange), data inputs to model components (grey), and generated outcomes (pink).

### 2.2.5. Likelihood Specification

For delivery-specific PPH counts, we specified the likelihood as follows. For each country c in year t, the numbers of vaginal and caesarean births were derived from total births and sub-regional caesarean section rates as shown in equation 15. The caesarean section rate for each UN sub-region s[c]containing country c at time t is denoted by $\rho^{CS}_{s[c],t}$and was taken from Betran et al., study[28]. Delivery mode-specific PPH counts were then obtained by applying the country-specific PPH rates from the hierarchical model (equations 7) to the corresponding birth counts (equations 15).

$$B^{VB}_{c,t} = B_{c,t} \times \left(1 - \rho^{CS}_{s[c],t}\right), \qquad B^{CS}_{c,t} = B_{c,t} \times \rho^{CS}_{s[c],t} \tag{15}$$

Where, country-specific PPH counts by VB $[N^{VB}_{c,t} = B^{VB}_{c,t} \times \pi^{VB}_{500,c,t}]$ and CS births $[N^{CS}_{c,t} = B^{CS}_{c,t} \times \pi^{CS}_{500,c,t}]$ were estimated which were then used to estimate total PPH cases as follows, $[N^{PPH}_{c,t} = N^{VB}_{c,t} + N^{CS}_{c,t}]$. Similarly, total PPH deaths per country were estimated by scaling the observed maternal deaths () with regional PPH death fractions $\mu^{\psi}_{r}$ as shown in equation 9. Then, deaths were allocated between VB and CS PPH cases using an odds ratio weighted allocation. The relative weighting was determined by the estimated odds ratio of PPH mortality comparing CS to VB (centred at OR = 2.18, log prior mean = 0.779) as shown in function 9a and 9b. We have also calculated delivery mode-specific case fatality ratios (CFRs) as the ratio of deaths to cases as follows:

$$CFR^{VB}_{c,t} = \max!\left(0, \frac{D^{VB}_{c,t}}{N^{VB}_{c,t}}\right), \qquad CFR^{CS}_{c,t} = \max!\left(0, \frac{D^{CS}_{c,t}}{N^{CS}_{c,t}}\right) \tag{16}$$

denotes the country and mode of delivery-specific annual PPH probabilities derived from the hierarchical model incorporating global priors, regional random effects, country-specific deviations, and ridge-regularised covariate effects (GDP per capita, antenatal care coverage, skilled birth attendance). Finally, country-level maternal deaths were modelled using a normal likelihood on the log scale,

$$\log(M_{c,t}) \sim N(\alpha_{global}^{deaths} + \alpha_{r[c]}^{deaths}, \sigma_{deaths})$$

(17)

where $\alpha_{r[c]}^{deaths}$ represents the PPH death fraction for the SDG region containing country c, derived from Cresswell et al.'s multi-country systematic review and Bayesian analysis[29]. Further, PPH-related deaths were allocated between VB and CS PPH cases using an odds ratio-weighted allocation that accounts for differential case-fatality risk by delivery mode as shown in equation 9a and 9b. Then, the total PPH-specific MMR (PPH deaths per 100,000 live births) were estimated as follows,

$$MMR_{c,t}^{PPH} = \frac{D_{c,t}^{PPH}}{B_{c,t}} \times 100{,}000$$

(18)

Where, $B_{c,t}$ represents all births and $D_{c,t}^{PPH}$ represents PPH-related deaths. Similarly, $MMR_{c,t}^{VB}$ VB-specific PPH MMR (VB PPH deaths per 100,000 vaginal births) and $MMR_{c,t}^{CS}$ CS-specific PPH MMR (CS PPH deaths per 100,000 caesarean births) were estimated as follows,

$$MMR_{c,t}^{VB} = \frac{D_{c,t}^{VB}}{B_{c,t}^{VB}} \times 100{,}000, \qquad MMR_{c,t}^{CS} = \frac{D_{c,t}^{CS}}{B_{c,t}^{CS}} \times 100{,}000$$

(19)

### 2.2.6. Model Validation and Sensitivity Analysis

Convergence of MCMC sampling was assessed using the Gelman–Rubin statistic ($\widehat{R}$ <1.05 indicating convergence) and bulk and tail effective sample sizes (ESS >400) (Figure S6). Across key parameters (global VB/CS PPH rates, variance components, PPH death odds ratio, CFR ratio), $\widehat{R}$ values were 1.002 and bulk/tail ESS with 3717 (Figure S7) for both baseline hierarchical and ridge regularised hierarchical model.

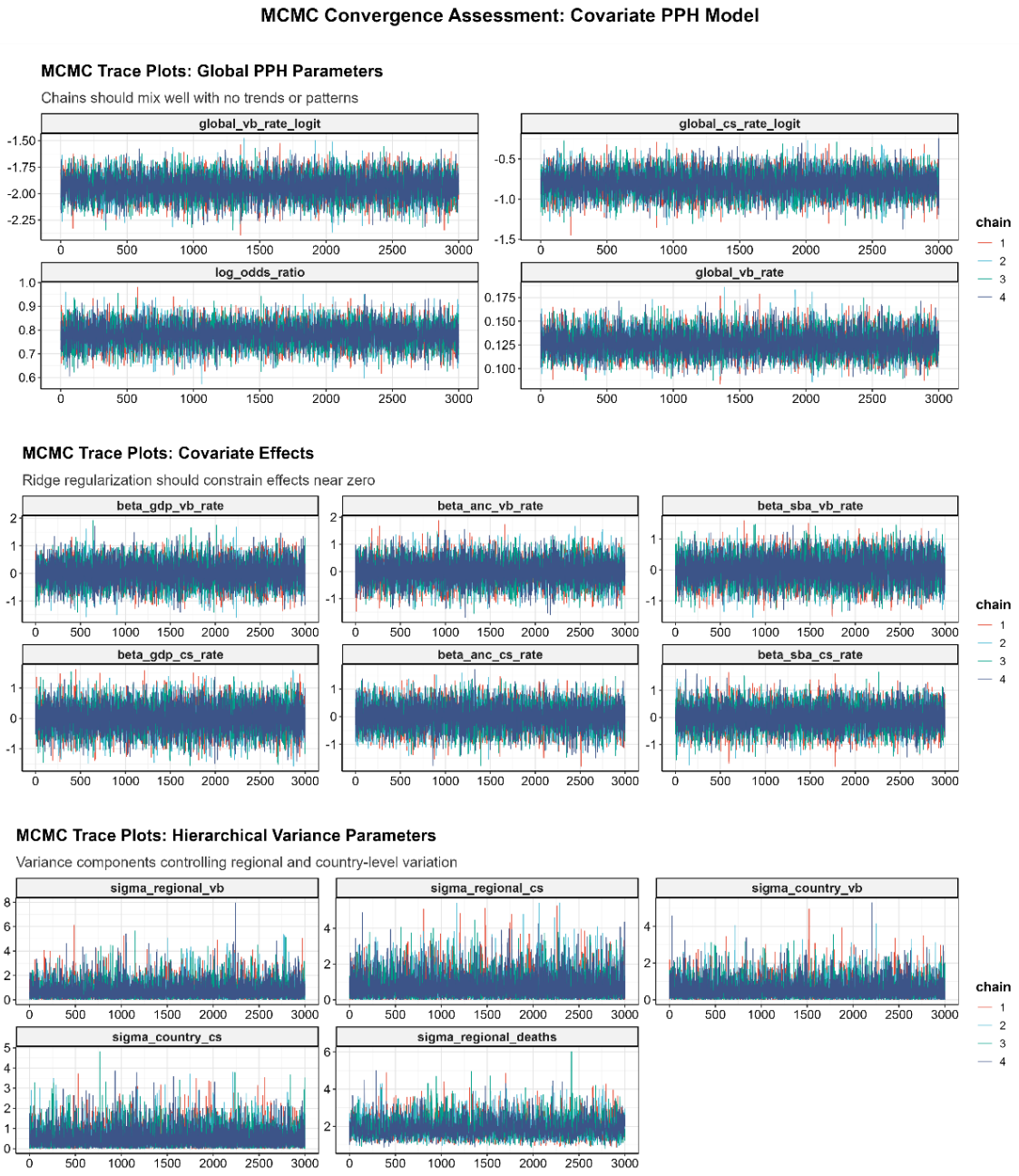


Figure S6. Markov chain Monte Carlo (MCMC) trace plots for key parameters of the ridge-regularised hierarchical Bayesian postpartum haemorrhage (PPH) burden model. Trace plots are shown for (A) global PPH parameters, (B) ridge-regularised covariate effects, and (C) hierarchical variance components. Each panel displays four chains with 3,000 post–warm-up iterations. Chains demonstrated good mixing with no discernible trends or patterns, and values remain stable across sampling iterations. Global parameters include the logit-scale priors for vaginal birth (VB) and caesarean section (CS) PPH rates, and the odds ratio for PPH deaths comparing CS with VB. Covariate effects (GDP per capita, antenatal care [ANC] coverage, and skilled birth attendance [SBA]) are appropriately constrained near zero by ridge regularisation to avoid over-fitting. Variance parameters (σ) capture residual heterogeneity at regional and country levels for VB, CS, and maternal deaths, and show no evidence of poor convergence.

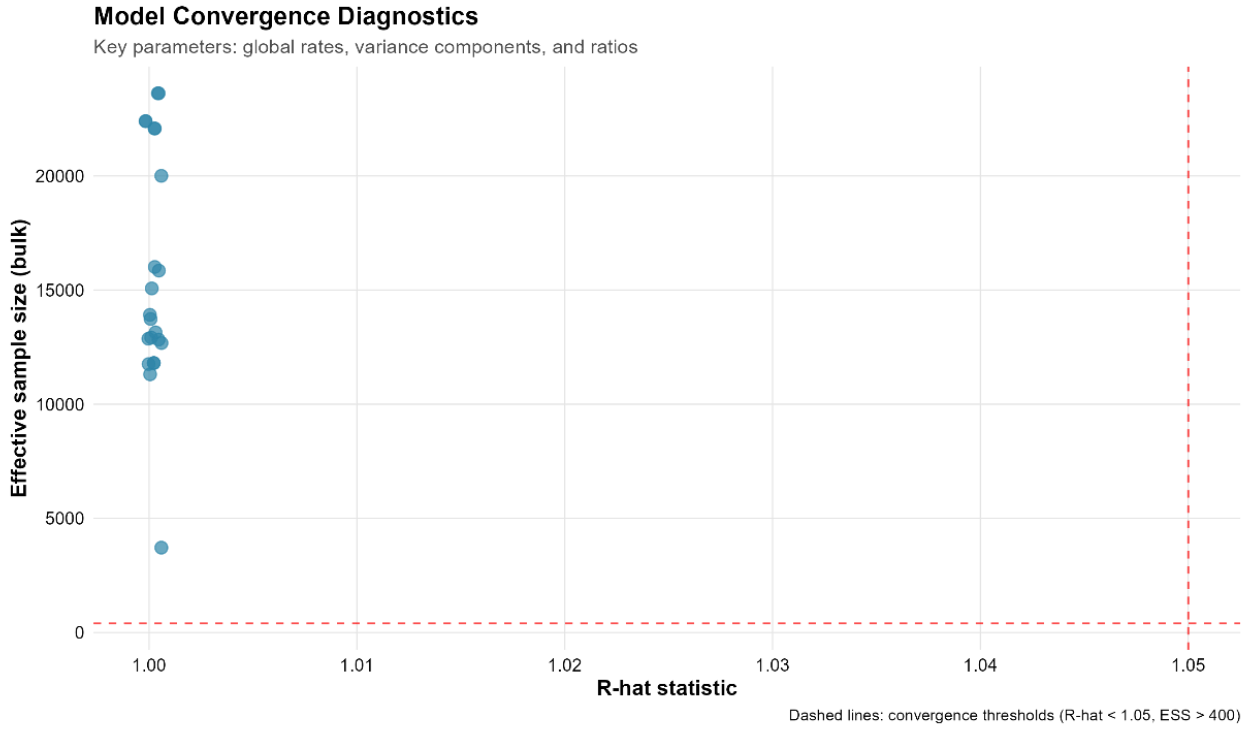


Figure S7. Convergence diagnostics where each point represents a study-level parameter, plotted by its $\widehat{R}$ (x-axis) and effective sample size (y-axis). All parameters had $\widehat{R}$ values <1.05 and ESS > 3000, indicating strong MCMC convergence. Both baseline hierarchical and covariate adjusted hierarchical model showed greater convergence and negligible differences in WAIC and LOOIC, i.e., WAIC: 1046.61 (SE: 21.90) and LOOIC: 1046.68 (SE: 21.91) in the baseline model vs WAIC: 1046.64 (SE: 21.90) and LOOIC: 1046.70 (SE: 21.90) for the ridge regularised covariate adjusted model respectively.

We compared models using out-of-sample predictive performance to identify the specification that generalised best. Our main measure was the expected log predictive density, which summarises how well each model predicts data not used in fitting. We also examined complementary information criteria that balance goodness-of-fit with model complexity. In addition, Pareto-k diagnostics were used to flag observations that might need closer examination or suggest areas where the model could be improved.

The posterior distributions of global PPH counts and deaths from the ridge-regularised hierarchical Bayesian model demonstrated how well the model integrated heterogeneous inputs to generate coherent burden estimates. For PPH counts, the posterior reflects uncertainty propagated from delivery-specific PPH priors, regional and country random effects, and covariate adjustments (Figure S8). The right-skewed shape indicates that while most posterior mass lies within ranges consistent with Stage 1 meta-analysis and regional birth volumes, the model also accommodates the possibility of higher global counts in settings with limited data [3].

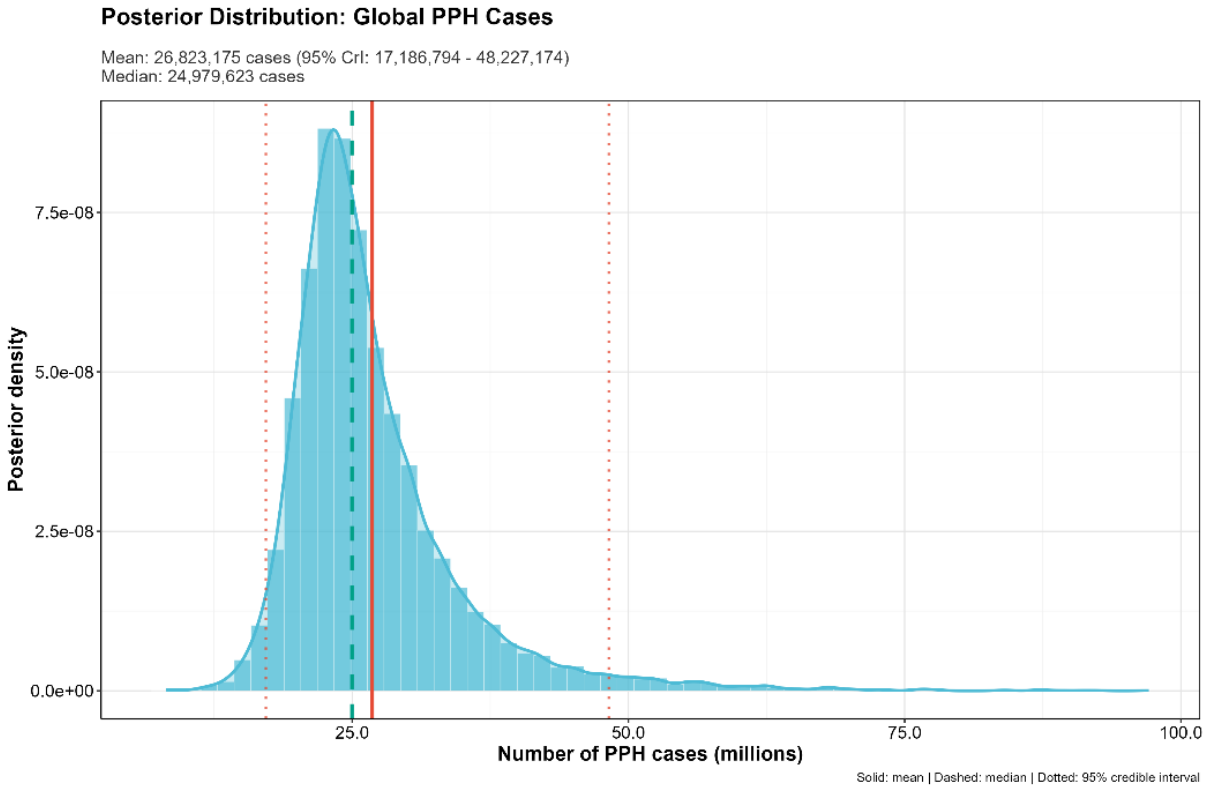


Figure S8. Posterior distribution of global PPH counts. Posterior density of global PPH case estimates (in millions). The mean was 26.8 million cases (95% CrI: 17.2- 48.2 million), with a median of 25.0 million. The right-skewed distribution reflects greater uncertainty in high-burden regions with sparse delivery-specific data. Vertical lines denote the posterior mean (solid), median (dashed), and 95% credible interval bounds (dotted).

For PPH deaths, the posterior distribution was tighter and more symmetric, reflecting the stronger constraints from MMEIG maternal death totals, SDG-region PPH death fractions, and the odds ratio prior linking caesarean and vaginal birth mortality[29].. The credible interval for mortality estimates suggests that these outcomes may be more tightly constrained by the

available data than the corresponding case estimates, although this interpretation should be made cautiously given the uncertainties inherent in both sources (Figure S9). Overall, the posterior distributions offer reassurance that the model behaves in a coherent way, with outputs that are generally consistent with existing evidence while still allowing for the considerable uncertainty surrounding these parameters.

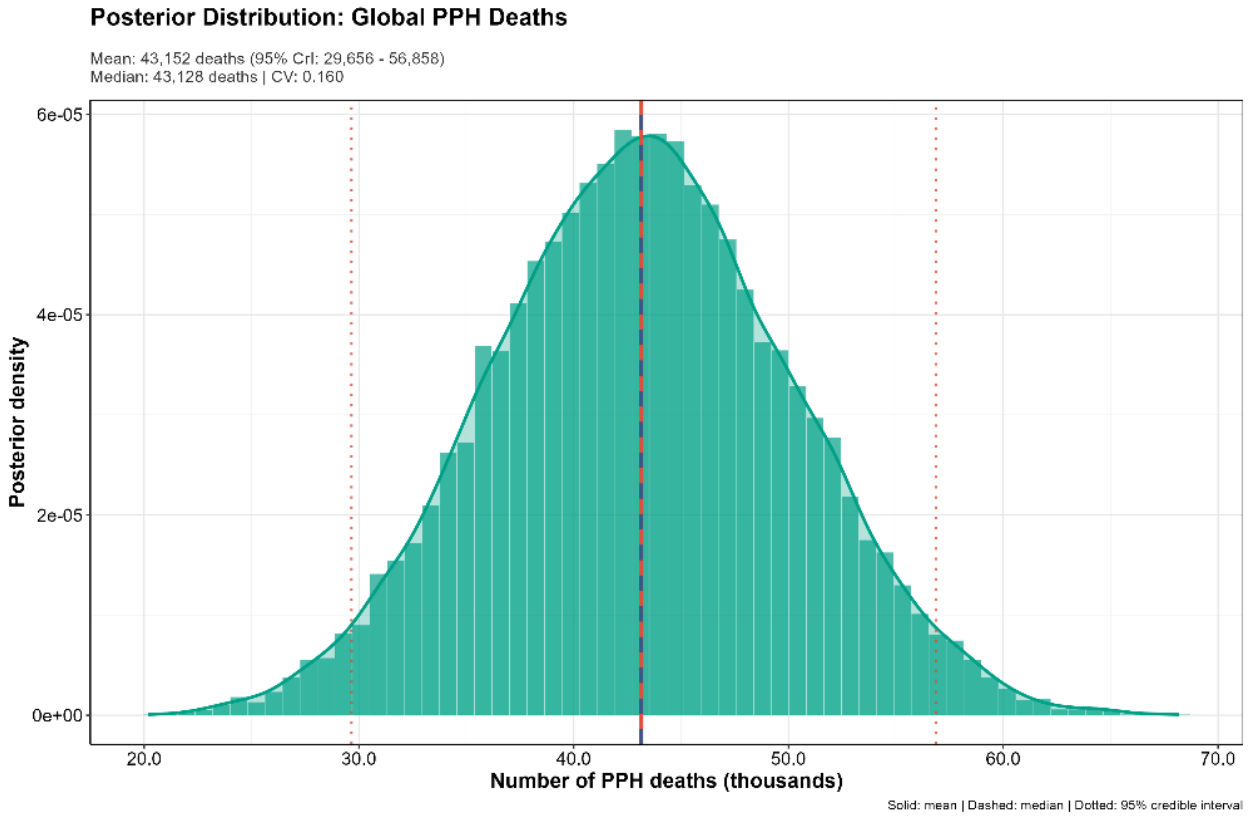


Figure S9. Posterior distribution of global PPH deaths. Posterior density of global PPH death estimates (in thousands). The mean was 43,152 deaths (95% CI: 29,656–56,858), with a median of 43,128 deaths and a coefficient of variation of 0.16. The distribution is symmetric, centred on the evidence-informed priors for maternal deaths and odds-ratio-constrained allocation by delivery mode. Vertical lines denote the posterior mean (solid), median (dashed), and 95% credible interval bounds (dotted).

### 2.2.7. R codes for Stage 2 Model for PPH counts and deaths

```
#Prior
global_vb_rate_logit ~ normal(-1.937, 0.119);
global_cs_rate_logit ~ normal(-0.805, 0.153);
```

```
log_odds_ratio ~ normal(0.779, 0.05);

#Liklihood
target += normal_lpdf(log(maternal_deaths[i]) |
log_death_linear_pred[i], sigma_deaths_obs)
```

### 3. Data Sources

#### 3.1. Data on Births

Total birth numbers were obtained from the United Nations World Population Prospects (WPP) (2024)[1]. The WPP compiles data from national censuses, vital registration systems, and sample surveys conducted between 1950- 2023, harmonised by the UN Population Division. We extracted country-level annual estimates of live births for the year 2023. Data are representative at the national level for all UN member states and territories. The full documentation of data sources underlying WPP 2024 is available online (World Population Prospects). The WPP birth estimates were the denominator for calculating population-based PPH counts and the baseline population at risk for PPH risk calculations[1].

#### 3.2. Data on Maternal Deaths

We obtained country-level maternal mortality estimates from the WHO, UNICEF, UNFPA, World Bank Group, and UNDESA Population Division report "Trends in Maternal Mortality: 2000 to 2023 from the Maternal Mortality Estimation Inter- Agency Group (MMEIG)(Maternal mortality ratio (per 100 000 live births).The MMEIG estimates are derived from multiple inputs, including civil registration and vital statistics (CRVS), sample registration systems, population censuses, household surveys, and specialised maternal mortality studies. The estimated maternal deaths were derived using a Bayesian statistical framework known as the Bayesian maternal mortality estimation model (BMat). The BMat functions were retrieved from GitHub (https://github.com/WorldHealthOrganization/bmat) for further understanding of the model structure[32]. In short, MMEIG maternal deaths formed the basis from which we estimated the number of PPH- related deaths by applying PPH-death fractions from Cresswell et al.[29].

### 3.3. Data on Caesarean Section Rates

We obtained sub-regional caesarean section rate estimates from the global database of CS trends published by Betran et al.,[28] in their Supplementary table 3. The CS rate projections were estimated using data from multiple sources including Demographic and Health Surveys (DHS), Multiple Indicator Cluster Surveys (MICS), national administrative data. A multilevel mixed-effects regression model was applied to generate annual estimates of CS rates where empirical data were limited and detailed methods were found elsewhere[28].

### 3.4. Covariate Data for Ridge model

GDP per capita data were obtained from World Bank World Development Indicators (GDP (current US$) | Data)[33], representing purchasing power parity adjusted estimates. These estimates provide indicators of healthcare resource availability and general economic capacity to invest in maternal health infrastructure and service quality. Data were log-transformed and standardised to improve model convergence and appropriate interpretation of coefficient estimates.

Antenatal care coverage data were obtained from WHO Global Health Observatory (Antenatal care coverage - at least four visits (%)[35]) and UNICEF global databases (Antenatal care - UNICEF DATA), representing the proportion of pregnant women receiving at least four antenatal care visits. This indicator provides insight into healthcare access patterns, preventive care quality, and opportunities for early risk identification that may influence PPH incidence.

Skilled birth attendance coverage data were obtained from WHO (Births attended by skilled health personnel (%)) and UNICEF databases (Skilled birth attendant - Proportion of births attended by skilled health personnel (MNCH_SAB) - UNICEF DATA)[34], representing the proportion of births attended by skilled health care professionals including doctors, nurses, or midwives. This indicator captured access to trained healthcare providers capable of recognising and providing initial management of PPH, representing a critical component of effective maternal healthcare systems. Data were logit-transformed and standardised for analysis.

### 3.5. Regional Mortality Pattern Data

PPH death fractions and uncertainty estimates were derived from Cresswell et al.'s systematic review and meta-analysis of WHO multi-country survey, vital registrations and MMEIG data[29], representing the proportion of maternal deaths attributable to postpartum haemorrhage within each SDG geographic region. These estimates provide regionally specific priors that reflect the substantial geographic variation in PPH mortality burden, with higher proportions observed in sub-Saharan Africa and South Asia compared to other regions.

### 3.6. Data Preprocessing and Covariate Treatment

All continuous covariates were standardized using z-score transformation, defined as $x_{std} = \frac{x-\bar{x}}{sd(x)}$ where $\bar{x}$ is the sample mean and sd(x) is the standard deviation across all countries. This standardisation facilitated direct comparison of effect sizes across covariates measured on different scales, such as GDP per capita (in US dollars) and maternal health service coverage indicators (expressed as percentages).

To address incomplete covariate data, we applied a structured, multi-stage imputation strategy designed to maximise representativeness and minimise bias:

- Primary temporal modelling: For countries that had only partial information on antenatal care or skilled birth attendance, we filled the gaps by estimating the missing years. To do this, we used several types of time-trend models, and we fitted each model separately to the data available for each country. The models included simple polynomial trends, approaches that smooth the data over time, and linear models. All of these models were fitted within a Bayesian framework. We used weakly informative priors that reflected patterns seen in neighbouring countries, and we gave lower weight to data points that were of poorer quality, such as those with small sample sizes and less reliable survey methods. For each country, we selected the best-performing model using leave-one-out cross-validation. The final projections captured two main sources of uncertainty. The first was model uncertainty, which reflects how much the fitted trends varied across the different draws from the posterior distribution. The second was extrapolation uncertainty, which grows naturally as the gap increases between the most recent data and the year we

are trying to estimate. We represented this by allowing the variance of the model residuals to increase gradually as the projection extended further beyond the last observed year.

- Secondary regional imputation: For countries with no available data on antenatal care or skilled birth attendance, we generated estimates by drawing on information from other countries in the same region with strong survey coverage. We first fitted a hierarchical model to all countries in each region that had observed data. This produced a regional distribution of likely coverage patterns over time. We then used this regional distribution as the prior for countries with no data at all, allowing us to derive a country-level estimate even in the absence of any direct observations.
- Quality adjustment: Each covariate value, whether directly observed or imputed, was given a quality score on a continuous scale from zero to one. This score reflected three equally weighted components. The first was the type of data source. Nationally representative surveys received the highest score, administrative data received a moderate score, and modelled estimates received lower scores. The second component reflected how recent the data were, with values close to the target year 2023 receiving higher scores and older data receiving progressively lower scores. The third component reflected sample size where this information was available, with larger and more reliable samples receiving higher scores. These three elements were combined to produce a single quality score for each covariate in each country and year. This score was then used to adjust the amount of uncertainty around imputed value before it entered the main model. In practical terms, high quality covariates carried the base level of uncertainty from the imputation model, while lower quality covariates were assigned a wider spread to reflect the greater uncertainty associated with them. This widening of the uncertainty interval grew larger as the quality score decreased. These adjusted variances were then carried forward into the main Bayesian hierarchical model.

Sensitivity analyses comparing results from complete case analysis and imputed datasets indicated minimal impact of the imputation procedure on model validity and parameter estimates, supporting the robustness of the analytical approach[24].

## 4. Model Outcomes and Interpretations

In summary, our ridge regularised hierarchical Bayesian framework produced internally consistent estimates of the global burden of postpartum haemorrhage. At the global level, the model yielded approximately 26.8 million PPH counts and 43,100 maternal deaths attributable to PPH in 2023, with uncertainty intervals reflecting data sparsity in some regions. The overall PPH-specific median maternal mortality ratio (PPH-MMR) was 32.6 per $100,000$ total births (80% CrI 26.0-39.3). When stratified by mode of delivery, the CS-PPH-MMR was 50.7 per $100,000$ caesarean births (80% CrI 32.0- 78.8), whereas the VB-PPH-MMR was 26.6 per $100,000$ vaginal births (80% CrI 17.6- 35.4). Regional patterns were consistent with known gradients in maternal health system capacity (Table S3 and Table S4), with the highest case fatality risks found in Sub-Saharan Africa (Figure 2). At the country level, Nigeria emerged as the largest contributor to global PPH-related deaths (Table S9). Together, the estimates provided a quantitative framework for prioritising global and national strategies to reduce PPH- related deaths and highlighted where the largest health improvements could be achieved.

**Table S3: SDG- Regional PPH counts stratified by delivery mode**

| SDG Regions | Mean CS-rates | Total PPH counts (median) | Total PPH counts (80% CrI) | VB PPH counts (median) | VB PPH counts (80% CrI) | CS PPH counts (median) | CS PPH counts (80% CrI) |
|---|---|---|---|---|---|---|---|
| Australia and New Zealand | 38.5 | 76448 | (43783 - 137717) | 28682 | (10809 - 72360) | 43806 | (19235 - 82031) |
| Central Asia and Southern Asia | 16.7 | 6701145 | (3993741 - 12559754) | 4182066 | (1835987 - 9748581) | 2326437 | (1125375 - 4153020) |
| Eastern Asia and Southeastern Asia | 33.3 | 4266650 | (2650448 - 7392399) | 1793448 | (827785 - 4041524) | 2302594 | (1155586 - 4106719) |
| Latin America and the Caribbean | 47.5 | 2144351 | (1337192 - 3461586) | 661331 | (311933 - 1387063) | 1416222 | (744824 - 2316693) |
| Northern America and Europe | 32.1 | 2050937 | (1313027 - 3446991) | 949907 | (440597 - 2091464) | 1036080 | (547764 - 1713684) |
| Oceania | 36.4 | 68901 | (40897 - 123215) | 27585 | (11454 - 66880) | 38230 | (17937 - 70840) |
| Sub-Saharan Africa | 6.1 | 5968853 | (3159394 - 11449091) | 5135099 | (2351919 - 10629139) | 778390 | (416871 - 1260888) |
| Western Asia and Northern Africa | 40.1 | 2537268 | (1596455 - 4139749) | 957811 | (451612 - 2036151) | 1482848 | (795744 - 2411829) |

Regional PPH counts posterior estimates derived from the PPH burden model (Stage 2 PPH burden model). CS: Caesarean Section; PPH: Postpartum Haemorrhage; VB: Vaginal Birth. Data were shown as posterior medians and 80% credible intervals (CrI). Wider credible intervals in certain regions were represented by the variability in the CS-rates and input data heterogeneity[28].

**Table S4: SDG- Regional PPH-related deaths stratified by delivery mode**

| SDG Region | Total PPH deaths (median) | Total PPH deaths (80% CrI) | Total PPH MMR (80% CrI) | VB PPH deaths (median) | VB PPH deaths (80% CrI) | VB PPH MMR (80% CrI) | CS PPH deaths (median) | CS PPH deaths (80% CrI) | CS PPH MMR (80% CrI) |
|---|---|---|---|---|---|---|---|---|---|
| Australia and New Zealand | 1 | (1 - 1) | 0.3 (0.2-0.4) | 0 | (0 - 1) | 0.1 (0.0-0.3) | 1 | (0 - 1) | 0.6 (0.3-0.8) |
| Central Asia and Southern Asia | 6624 | (4328 - 9006) | 16.9 (10.8-23.0) | 2872 | (1291 - 5093) | 9.0 (4.0-16.1) | 3439 | (1599 - 5735) | 46.5 (21.4-76.6) |
| Eastern Asia and Southeastern Asia | 1957 | (1489 - 2424) | 9.4 (7.1-11.7) | 765 | (364 - 1329) | 5.7 (2.7-9.9) | 1141 | (621 - 1674) | 15.5 (8.5-22.8) |
| Latin America and the Caribbean | 883 | (824 - 940) | 9.4 (8.8-10.0) | 169 | (70 - 362) | 3.4 (1.4-7.1) | 710 | (519 - 820) | 16.0 (11.8-18.5) |
| Northern America and Europe | 102 | (90 - 116) | 1.0 (0.9-1.1) | 31 | (13 - 59) | 0.4 (0.2-0.8) | 70 | (42 - 91) | 2.2 (1.3-2.8) |
| Oceania | 71 | (40 - 105) | 20.9 (12.1-31.2) | 17 | (5 - 41) | 7.9 (2.7-19.4) | 49 | (24 - 81) | 40.0 (19.0-66.6) |
| Sub-Saharan Africa | 31836 | (23322 - 40351) | 79.3 (58.1-100.7) | 22680 | (13563 - 31632) | 60.1 (36.7-82.9) | 8205 | (3304 - 16474) | 337.9 (130.8-674.7) |
| Western Asia and | 1677 | (1262 - 2100) | 14.3 (10.7-17.8) | 397 | (161 - 838) | 5.6 (2.2-11.9) | 1229 | (749 - 1674) | 26.3 (16.1-35.9) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Northern Africa | | | | | | | | | |

Regional PPH -related deaths posterior estimates derived from the PPH burden model. CS: Caesarean Section; PPH: Postpartum Haemorrhage; VB: Vaginal Birth. Data were shown as posterior medians and 80% credible intervals for PPH-related deaths. MMR (maternal mortality ratio) denotes the number of maternal deaths per 100,000 live births. Delivery mode-specific MMRs (i.e., VB-MMR, CS-MMR) were estimated using mode-specific deaths and births as the numerator and denominator, respectively from each posterior draws from the Stage 2 PPH burden model. SDG region-level estimates have wide credible intervals, reflecting uncertainty from sparse data, and multiple modelling stages.

## 5. Model Limitations

Our Bayesian hierarchical modeling approach has several limitations that need to be addressed. Firstly, the generalisability of underlying CS-PPH risk estimates, i.e., included studies from high-income settings for objectively measured CS-PPH ≥500mL may not reflect risk of PPH in low- and middle- income countries (LMICs). Secondly, the temporal variations between UN birth data (2023), MMEIG (2023), and covariate data collected in earlier years, may not capture healthcare changes over time. Similarly, regional assignment of PPH death fractions may not capture country-specific mortality patterns. Whilst the methodological framework using ridge regularisation in Bayesian estimation reduce over-fitting, this approach may over-shrink covariate effects in heterogeneous regions. This could underestimate the influence of country-specific healthcare factors. Finally, data on delivery mode-specific PPH mortality reports for estimating the caesarean versus vaginal death weighting is limited. In addition, the included studies varied in design, representativeness, and completeness, and did not cover all global regions. While the death weight was used to inform the model on relative allocation rather than absolute PPH-related deaths, the small number of input sources increased the uncertainty of the delivery-mode specific death estimates. Furthermore, a significant limitation of the PPH burden model is the aggregation bias. Our model estimates showed higher PPH-specific CS-MMR per birth. This is mainly due to differing denominators and differences in case mix, health-system resources, and clinical indications of caesarean births. Therefore, delivery-mode-specific estimates should be interpreted cautiously. This underscores the need for more comprehensive, high-quality data reporting on delivery mode-specific maternal mortality.

## 6. GATHER Statement

The hierarchical Bayesian modeling approach we used for estimating global, regional, sub-regional, and country-specific postpartum haemorrhage (PPH) burden (i.e., PPH counts and PPH-related deaths) followed the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) framework[46]. Table S5 outlines the data collection, data processing, model specification and prior selection, computational implementation, convergence assessment, and uncertainty propagation used in the modeling approach. Detailed mathematical notation, convergence diagnostics, and sensitivity analyses examining the robustness of modeling assumptions are reported in the corresponding sections.

## 7. BARG Checklist

We adhered to the Bayesian Analysis Reporting Guidelines (BARG), which provide a structured framework to ensure clarity, transparency, and reproducibility in contemporary Bayesian analyses[44]. Table S6 showed the details of the Bayesian analysis, including descriptions of all variables, the likelihood, priors with justification, formal model specifications, hierarchical structure, software, and full MCMC procedures with convergence diagnostics and posterior predictive checks. We also reported posterior summaries with credible intervals, compared priors and posteriors, documented model selection and sensitivity analyses, and ensured full code and data availability in the relevant sections.

**Table S5: Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) checklist[46]**

| Item | Checklist description | Description of use in the Bayesian analysis |
|---|---|---|
| Objectives and funding | | |
| 1 | Define the indicators, populations, and time period(s) for which estimates were made. | Indicators:<br><br>1.Postpartum haemorrhage (PPH) ≥500 mL following caesarean section (CS)<br>2. Total PPH counts (≥500 mL), stratified by delivery mode (vaginal birth vs caesarean section)<br>3.PPH-related maternal deaths, stratified by delivery mode (vaginal birth vs caesarean section)<br><br>Estimates were produced at the country- and territory- level for all United Nations (UN) Member States and territories (n = 235), these were aggregated to 15 UN sub-regions, 8 Sustainable Development Goal (SDG) regions, and global levels. The reference population consisted of all women giving birth in 2023. The model incorporated gross domestic product (GDP) per capita, antenatal care (ANC) coverage with a minimum of four visits, and skilled birth attendance (SBA) coverage as country-level covariates |
| 2 | List funding sources for the work. | Reported in the manuscript |
| Data inputs: For all data inputs obtained from the publicly available sources and integrated within the analysis | | |
| 3 | Describe how data were identified and accessed. | We identified and accessed the following sources:<br><br>1. A literature search of objectively measured blood loss estimation for PPH rates in vaginal and caesarean section births[3];<br>2. Population-level data were drawn from publicly available sources as follows: Annual births from the UN World Population Prospects 2024[1];<br>3. Maternal death estimates were derived from the WHO MMEIG 2023 modeled outputs (functions retrieved from GitHub)[32];<br>4. Caesarean section rate projections from UN-sub-regional level data[28];<br>5. Covariate indicators such as GDP per capita, ANC, and SBA from the World Bank, WHO, and UNICEF global databases.<br><br>All data sources are publicly accessible and cited in the reference list. |

| | | |
|---|---|---|
| 4 | Specify inclusion and exclusion criteria. | We included country-specific data on total births (UN World Population Prospects) and maternal deaths (WHO MMEIG estimates) for countries with complete population-level denominators enabling calculation of nationally representative maternal mortality ratios. We excluded single-facility studies, case reports, subnational studies lacking clear population boundaries, and any data sources without appropriate population denominators (defined as total live births, total births, or national population estimates allowing for standardised maternal mortality indicator calculation according to WHO definitions) |
| 5 | Provide information on all data sources (type of source, geographic location, years covered, population represented, and reference). | We used the following data sources:<br><br>1. Country-specific total births from the UN World Population Prospects 2024 for the year 2023[1];<br>2. Total maternal deaths from MMEIG for the year 2023[32];<br>3. Caesarean section rate projections from Bayesian model estimates for the years between 2021 and 2025[28];<br>4. Gross domestic product (GDP) per capita[33];<br>5. Antenatal care (ANC) coverage (minimum of 4 visits)[35];<br>6. Skilled birth attendance coverage for the years 2022-2023[34] |
| 6 | Describe the methods for extracting data and any data processing steps. | Total births, maternal deaths, and caesarean section rates were extracted from published databases[28,32,47].<br>Country-year identifiers were harmonised;<br>Maternal death estimates were directly extracted from the WHO MMEIG 2023 dataset;<br>Caesarean section rate projections were applied at 15 UN sub-regional level;<br>GDP was log-transformed; ANC and SBA were logit-transformed; All covariates were standardised |
| Data analysis: | | |
| 7 | Provide a conceptual overview of the model or analysis method. | We used a Bayesian hierarchical model estimating country-specific PPH counts and deaths stratified by mode of delivery. The model integrates global PPH rate priors, UN sub-regional caesarean section rates, SDG-regional PPH death fractions, and country-specific covariates through log-linear death likelihood with ridge-regularised covariate effects.<br>Prior specifications were from randomised controlled trials (RCTs)[4,5] and systematic review and meta-analysis[3,29] as published elsewhere. |
| 8 | Provide detailed description of all steps of analysis, estimation | We used Bayesian hierarchical estimation implemented in Stan (version 2.38.0) via CmdStanR interface.<br>Three-level hierarchy was implemented:<br><br>1. Global population parameters,<br>2. SDG-regional random effects, |

| | | |
|---|---|---|
| | methods, and software used. | 3. country-specific deviations.<br><br>Non-centred parameterization for Markov Chain Monte Carlo (MCMC) efficiency was implemented.<br>We used:<br><br>1. Log-linear likelihood for maternal deaths with hierarchical linear predictor;<br>2. Ridge regularisation for covariate effects;<br>3. MCMC sampling: 4 chains, 6000 warmups, 3000 sampling iterations;<br>4. Convergence assessed via R-hat and effective sample size |
| 9 | Specify how covariates were selected and incorporated. | We used the following covariates as they can reflect the levels of maternity care: GDP per capita (log-transformed, standardised), ANC (logit-transformed, standardised), and SBA (logit-transformed, standardised). Covariates were incorporated as ridge-penalized effects (λ=5.0) on logit-scale PPH rate parameters to prevent overfitting |
| 10 | Describe how uncertainty was calculated. | We assessed uncertainty propagation in the following ways:<br><br>1. Parameter uncertainty - through Bayesian posterior distributions from MCMC sampling (3000 draws per parameter across 4 chains);<br>2. Sampling uncertainty - from Monte Carlo estimation;<br>3. Model sensitivity - assessed through prior specification variations (±20%), covariate inclusion comparison, and alternative ridge penalties.<br><br>We set 80%credible intervals to show parameter and sampling uncertainty.<br>All country estimates include hierarchical borrowing uncertainty through regional random effects. |
| 11 | Provide details of any data adjustments (e.g. outlier exclusion, redistribution). | Data preprocessing: Caesarean section rates >60% were truncated to 60% (n=3 countries), where the upper bound for caesarean section rates was applied based on the model estimates by Betran et al (2021)[28]; Missing covariate data handling for ANC and SBA coverage estimates were processed using temporal modeling approaches. For countries with historical data (1990-2023), we applied Bayesian-informed temporal weighting using polynomial models, exponential smoothing, and linear trend analysis with uncertainty quantification. For countries without historical data, regional median values were assigned based on patterns from countries with robust survey data within each SDG region. PPH death fractions at SDG region-level estimates were assigned with region-specific standard deviations. Extreme values were checked by posterior predictive checks |
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| Results and discussion | | |
| 12 | Provide estimates with measures of uncertainty. | Outcomes were presented at three geographic levels: 235 countries, 8 SDG regions, and global totals. For each level, reported estimates include: PPH rates at vaginal birth and caesarean section, absolute PPH counts, and PPH-related deaths. All estimates were presented with posterior means, medians, and 80% credible intervals from Bayesian posterior distributions |
| 13 | Interpret results in light of existing evidence. | External validation was conducted by comparison of country- specific estimates with: published reports, confidential enquiry reports[36,37,48,49], the World Health Organisation (WHO) mortality database[50] and the Global Health Data Exchange[51]; Caesarean section rates were compared to UNICEF data[52] |
| 14 | Discuss limitations of the estimates. | The data source for caesarean section PPH ≥1000mL parameters was limited in geographic and health-system diversity, which may reduce the generalisability of the estimates.<br>Temporal modelling of the missing covariates such as antenatal coverage and skilled birth attendance with regional imputation might vary in data quality across countries.<br>Regional PPH death fractions may not capture country-specific mortality patterns within SDG regions.<br>CS rate estimates derived from Betran et al[28]., may not capture within-region heterogeneity. |
| Data and code availability | | |
| 15 | Provide information on how to access input data. | Primary data sources are publicly available: UN Maternal Mortality Estimation Inter-agency Group (MMEIG) 2023 estimates[32]; UN Population Division World Population Prospects 2024 for birth denominators[1]; World Bank Development Indicators for GDP per capita data; Healthcare coverage indicators obtained from WHO/UNICEF Joint Monitoring Programme reports 2024[34,35] |
| 16 | Provide information on how to access analytical or statistical code. | The complete analytical pipeline is outlined in the corresponding sections:<br>All Stan model files (stan format) provided in the supplementary appendix;<br>R analysis scripts (R version 4.3.3) for data preparation, MCMC diagnostics, convergence assessment, and results extraction will be accessible in the GitHub repository (URL will be provided upon request);<br>All the code which was used followed reproducible research standards and used sessionInfo() documentation |

**Table S6: Bayesian Analysis Reporting Guidelines (BARG) checklist[53]**

| Item | Checklist | Description in supplementary appendix |
|---|---|---|
| **1A** | Describe data variables | Section 2.1 (Stage 1), Section 2.2.3 (Stage 2): study-level PPH rates, country-level births, maternal deaths, CS rates, covariates (GDP, ANC, SBA). Detailed data source were showed in GATHER statement |
| **1B** | Specify likelihood function | Section 2.1.5: Beta likelihood (Eq 5) with overdispersion (φ). Section 2.2.5: Normal likelihood on log-scale for maternal deaths (Eq 17) |
| **1C** | State priors with justification | Section 2.1.4: Informative priors from RCTs and a weak prior for μ parameters. Section 2.2.3: Stage 1 posteriors as Stage 2 priors (Eq 7a- 7b). Ridge priors $\gamma \sim N(0, 1/\sqrt{\lambda})$ (Eq 14) |
| **1D** | Provide formal model specification | Full mathematical notation in Sections 2.1 and 2.2 with 17 equations. Stan code attached. |
| **1E** | Explain hierarchical structure | Three-level hierarchy: global - SDG region - country (Eq 12-13). Non-centred parameterisation (Eq 6). Variance components: σ_region ~ Exp(1.5), σ_country ~ Exp(2.0) |
| **2A** | Report software and version | cmdStan via cmdstanr and posterior packages in R (Section 2.1.5) |
| **2B** | Report MCMC details | Stage 1: 4 chains, 2,500 iterations (1,000 warmup), 6,000 posterior samples. Stage 2: equivalent specification |
| **2C** | Report convergence diagnostics | Stage 1: $\hat{R}$, ESS >200, trace plots (Figure S1). Stage 2: $\hat{R}$ <1.05, ESS >400 (3,717 bulk/tail), Figures S6-S7 |
| **3A** | Posterior predictive checks | Stage 1: PPCs for mean, SD, and maximum across outcomes (Figure S2). Stage 2: Posterior distributions of global PPH counts/deaths (Figure S8) |
| **3B** | Report posterior summaries with CI | Stage 1: CS-PPH 30.9% (95% CI: 24.9-37.6%); Stage 2: country/regional/global estimates with 95% CI. Table S1: RMSE, MAE, coverage |

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| **3C** | Prior-posterior comparison | Stage 1: Prior vs posterior distributions (Figure S3). Posterior shifts documented, confirming data-driven estimation |
| **4A** | Model selection criteria | Stage 2: LOO-CV with PSIS, WAIC, LOO-IC, Pareto-k diagnostics (Figure S7) |
| **5A** | Sensitivity to prior specification | Stage 1: 0.7 scaling factor on prior SDs to test learning from data. Stage 2: $\lambda$ selected through prior sensitivity analysis. Prior–posterior overlap examined (Figure S3) |
| **5B** | Sensitivity to model specification | Stage 2: Baseline hierarchical vs ridge-regularised model comparison (Section 2.2.6) |
| **6A** | Code availability | Stan model code is attached for both Stage 1 and Stage 2 model |
| **6B** | Data availability | WHO, UNICEF, World Bank publicly accessible data sources. CS rate projections from Betran et al., 2021. PPH death fractions from Cresswell et al., 2025 (Detailed reporting in GATHER statement in Table S5) |

## Economic Burden of Postpartum Haemorrhage

### Direct health care costs

From a health provider perspective, the annual global economic burden of PPH was estimated using an ingredients-based approach, based on the different medical procedures required for PPH management, their frequency of occurrence and associated unit costs (e.g. additional oxytocin, tranexamic acid, blood transfusion, uterine balloon tamponade, hysterectomy, transfer to higher level facilities or ICU admission).

For each country, the analysis considered: the number of women experiencing PPH; the proportion of women with PPH who have access to care (using coverage of skilled birth attendants[54] as a proxy); and among those who receive care, the proportion who require different types of medical procedures. Costs were estimated for one year (2023) and are presented in 2023 US$.

A targeted review was undertaken to identify available unit cost data for the above treatment components. We search Ovid-Medline on 17 February 2026 for studies published since 2015, using terms “PPH” OR “maternal haemorrhage” combined with “costs” OR “economics,” along with broader terms related to cost analysis and cost-benefit analysis. Limited studies were identified with data to inform cost estimates for the specific treatment components. The most relevant were a cost-effectiveness analysis of the E-MOTIVE trial (in Kenya, Nigeria, South Africa, Tanzania)[55] and a cost-effectiveness analysis of uterotonic drugs for the prevention of PPH in the UK[56]. Using these studies to broadly disaggregate unit costs into low- and middle-income versus high-income countries respectively, when weighted for the expected frequency of occurrence of each treatment component (details in Table 8), the mean cost per PPH in 2023 US$ was $71.60 (range $14.46–322.90) in low- and middle-income countries and US$730.78 (range 575.49–1012.43) in high-income countries. Other studies reported mean costs of PPH management, but often in the context of a specific type of PPH, including varying cost components, or not in comparison to births without PPH. For low- and middle-income countries, the above range using an ingredient-based approach is consistent with other studies reporting mean cost per PPH, including $30.3–127.4 (in 2018 US$) from a systematic review on costs of managing pregnancy and birth-related complications in sub-Saharan Africa[57]; a mean $26.9 (in

2018 US$) from the CHAMPION study in India, Kenya, Nigeria and Uganda[58]; and mean costs of $37–59 for atonic PPH in India (in 2017/18 US$), depending on setting and interventions[59]. For high-income countries, there are significant variations between the UK[56,60], USA[61], Australia[62] and France[63]. As the identified cost data were not adequate to assign country- and health-system-specific costs, we selected to approximate global costs based on a simple multiplicative model that only distinguished unit costs between high-income versus low-and middle-income country classifications. Therefore, a limitation of the analysis is that it does not capture the extreme heterogeneity across settings. Further work is needed to systematically review cost estimates for PPH treatment and understand how these vary across countries.

**Societal costs from disability-adjusted life years**

From a societal perspective, a value of statistical life year approach was taken to estimate the annual global economic burden of PPH-attributable disability-adjusted life years (DALYs). The analysis estimated total years of life lost due to a single year (2023) of PPH mortality, based on country-specific female health-adjusted life expectancy at mean age of pregnancy[64]. For non-fatal PPH, disutility weights for either "PPH>1000ml" and "PPH<1000ml"[65] were assigned for a period of six weeks[55]. DALYs were valued at average GDP per capita[33], weighted across countries according to PPH DALY burden, with 3% per annum discounting applied to future years of life lost.

**Inputs and sources**

Inputs for the calculations are shown in Table, **Error! Reference source not found.**, and

**Table** . Uncertainty intervals were generated using multivariate probabilistic sampling of parameters from their ranges.

**Results**

In 2023, the global economic burden of PPH was estimated to be US$3.6 billion ($3.2–6.2 billion) to health systems and US$6.8 billion ($6.2–7.5 billion) to society, totalling US$10.4 billion ($9.8–13.2 billion). These are likely to be underestimates, as they do not include medium- or longer-term morbidity from PPH, and are not exhaustive in the types of medical procedures considered. They also do not include costs to women, which are an additional economic burden to society and can be catastrophic for some individuals.

**Sensitivity analyses**

A sensitivity analysis was conducted to consider different approaches to estimating expected years of life remaining. When values from Singaporean women (who in 2023 had the longest life expectancy) were applied to all countries equally, the annual societal costs increased from US$6.8 billion to US$7.1 billion.

We also tested using a different proxy for the country-specific proportion of PPH to apply treatment costs to. When the proportion of health facility births was used[66], which is slightly lower than skilled birth attendance[54], the annual direct health costs decreased slightly but were the same to one decimal place (US$3.6 billion).

**Table S7: Parameters used to estimate the economic burden of postpartum haemorrhage (PPH)**

| Parameter | Value | Geographic disaggregation | Source |
|---|---|---|---|
| Number of births (2023) | **Error! Not a valid result for table.** | Country-specific | Country-specific total births from the UN World Population Prospects 2024 for the year 2023[1] |
| Number of women with PPH (2023) | **Error! Not a valid result for table.** | Country-specific | Estimates from Stage 2 Bayesian hierarchical model (function 16) |

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|---|---|---|---|
| Coverage of skilled birth attendants (most recent year) | **Error! Not a valid result for table.**9 | Country-specific | World Health Organization, Global Health Observatory[54] |
| Maternal deaths due to PPH (2023) | **Error! Not a valid result for table.**9 | Country-specific | Estimates from Stage 2 Bayesian hierarchical model (function 17) |
| Mean age of pregnancy (2023) | **Error! Not a valid result for table.**9 | Country-specific | World Bank, World Development Indicators[67] |
| Remaining health-adjusted life expectancy at age of maternal death | **Error! Not a valid result for table.**9 | Country-specific | Female health-adjusted life expectancy at mean age of pregnancy (Institute of Health Metrics and Evaluation 2021 Global Burden of Disease analysis[64]) |
| Proportion of PPH that is >1000ml | 26.7% | Global | Based on:<br>—26.2% for vaginal births (from systematic review[3], PPH prevalence of 12.6% and severe PPH of 3.3%);<br>—27.5% for caesarean births (30.9% estimated >500ml blood loss and 8.5% >1000ml blood loss[3]);<br>—Weighted sum of 37.7% of PPH for caesarean births globally |
| Disutility weight: PPH with blood loss 500-1000ml | 0.1143 (0.0779–0.1587) | Global | Institute of Health Metrics and Evaluation[65] |
| Disutility weight: PPH with blood loss >1000ml | 0.3242 (0.2197–0.4418) | Global | Institute of Health Metrics and Evaluation[65] |
| Duration PPH disutility applied for | 6 weeks | Global | Consistent with E-MOTIVE cost-effectiveness analysis[55] |
| GDP per capita (2023) | **Error! Not a valid result for table.**9 | Country-specific | World Bank, World Development Indicators[33] |
| Proportion of women with PPH who require different medical procedures | Table S8 | High-income versus low- and middle-income[68] | Table S8 footnotes |
| Unit cost of different medical procedures | Table S8 | High-income versus low- | Table S8 footnotes |

| | | | |
|---|---|---|---|
| | | and middle-income) | |

Parameters used to estimate the economic burden of postpartum haemorrhage (PPH).

**Table S8: Selected medical procedures involved postpartum haemorrhage (PPH) management, as well as their unit costs and frequency among women with PPH.**

Inputs are disaggregated by country income status (low- and middle-income countries (LMIC) versus high-income countries (HIC).

| Procedure or outcome | LMIC cost (2023 US$) | Proportion of women in LMICs with PPH who experience procedure or outcome | HIC cost (2023 US$) | Proportion of women in HICs with PPH who experience procedure or outcome |
|---|---|---|---|---|
| Oxytocin | $1.30^ | 93% ψ | $1.64 # | 93% ‡ |
| Tranexamic acid | $3.32^ ($3.14, $3.68) | 92% ψ | $3.32 ‡ ($3.14, $3.68) | 92% ‡ |
| Intravenous fluids | $0.96^ | 93% ψ | $0.96 ‡ | 93% ‡ |
| Blood transfusion | $128.96^ ($41.68, $300.09) | 16.70% χ (11.60%, 22.60%) | $603.85 & ($603.85, $1192.91) | 10.40% χ (8.20%, 12.90%) |
| Non-pneumatic anti-shock garment use | $1.34^ ($1.22, $1.60) | 0.56% ψ (0.28%, 1.12%) | | |

| | | | | |
|---|---|---|---|---|
| Uterine balloon tamponade | $2.59^ ($0.97, $7.18) | 5.90% χ (4.40%, 7.60%) | $2304.76 # | 2.50% χ (0.60%, 5.60%) |
| Transfer to higher level facility | $31.94^ ($15.09, $56.93) | 0.90% χ (0.10%, 2.20%) | | |
| Hysterectomy | $499.84^ ($144.47, $1393.07) | 2.60% χ (1.20%, 4.30%) | $6804.72 # | 1.70% χ (0.90%, 2.70%) |
| Additional day in hospital (estimated one or more days) | $35.75^ ($5.83, $114.68) | 51.90% θ (49.60%, 54.10%) | $792.88 Δ | 51.90% θ (49.60%, 54.10%) |
| Prolonged stay in hospital (estimated four or more days) | $107.24 φ ($17.50, $344.04) | 2.40% θ (2.00%, 2.70%) | $2378.65 Δ | 2.40% θ (2.00%, 2.70%) |
| ICU admission | $238.90^ ($44.79, $746.57) | 5.40% χ (0.10%, 16.70%) | $792.88Ω | 2.60% χ (0.60%, 5.90%) |

Selected medical procedures involved postpartum haemorrhage (PPH) management, as well as their unit costs and frequency among women with PPH.

^ E-MOTIVE cost-effectiveness analysis[55]; point estimate, lower bound and upper bound taken as the mean, minimum and maximum across the four countries (Kenya, Nigeria, South Africa, Tanzania) respectively. 2022 US$ converted to 2023 US$[69]

φ Costed as three additional days (so total four days when combined with category above)

ψ Participant data from E-MOTIVE[4]

χ Systematic review on consequences of PPH

θ Systematic review on consequences of PPH. For HIC, the pooled percentage is based on two studies from US; for LMIC, the pooled percentage is based on one study from Nigeria.

# Pickering et al.[56] UK analysis. 2016 pounds converted to 2023 US$[69].

‡ Assuming the same for high income countries as low- and middle-income countries.

& Pickering et al.[56] UK analysis. The analysis estimated £171.84 (1st unit) and £163.63 (subsequent units) and assumed two units of blood given (used as point estimate and lower bound) and an additional two units of blood for more severe cases (upper bound). 2016 pounds converted to 2023 US$[69].

Δ Pickering et al.[56] UK analysis. Excess bed day cost for PPH. Costing includes one additional day for "one or more day" category, and three additional days (hence total of four days) for "four or more days" category. 2016 pounds converted to 2023 US$[69].

Ω Assumed same as average additional days in hospital.

**Table S9: Country-specific parameters used to estimate the economic burden of postpartum haemorrhage (PPH)**

| Country | Number of women giving birth (2023) | Estimated number of women with PPH (2023) | Skilled birth attendance (most recent year) | Estimated maternal deaths due to PPH (2023) | Estimated MMR due to PPH (2023) | Estimated VB-MMR due to PPH (2023) | Estimated CS-MMR due to PPH (2023) | Average age of pregnancy[67] | Remaining health-adjusted life expectancy among | GDP per capita[33] (2023) |
|---|---|---|---|---|---|---|---|---|---|---|
| AFG | 1,469,029 | 289,574 | 68% | 1,191 | 81 | 42.5 | 219.6 | 30.4 | 28 (25, 31) | $414 |
| ALB | 28,803 | 6,683 | 100% | <5 | 0.6 | 0.2 | 1.3 | 29.1 | 45 (42, 48) | $8,575 |
| DZA | 905,981 | 210,109 | 99% | 108 | 12 | 4.4 | 22.7 | 31.5 | 38 (35, 40) | $5,364 |
| ASM | 1,000 | 228 | 100% | <5 | 12.7 | 3.9 | 24.1 | 29.4 | 40 (37, 43) | $18,017 |
| AND | 1,000 | 232 | 100% | <5 | 9.4 | 0 | 0 | 32.5 | 44 (41, 48) | $46,812 |
| AGO | 1,381,370 | 240,514 | 50% | 457 | 33.1 | 25.1 | 134.2 | 28.6 | 35 (32, 38) | $2,310 |
| ATG | 1,106 | 272 | 99% | <5 | 11.5 | 3.7 | 19.9 | 28.3 | 44 (41, 46) | $21,495 |
| ARG | 503,823 | 123,614 | 99% | 22 | 4.2 | 1.4 | 7.3 | 29.1 | 45 (42, 47) | $14,187 |
| ARM | 34,668 | 8,097 | 100% | <5 | 3.7 | 1.4 | 6.9 | 27.8 | 45 (42, 47) | $8,125 |
| AUS | 304,340 | 70,800 | 99% | <5 | 0.2 | 0.1 | 0.4 | 31.4 | 44 (41, 47) | $64,836 |
| AUT | 77,054 | 16,667 | 98% | <5 | 0.6 | 0.3 | 1.3 | 31.2 | 44 (41, 46) | $56,034 |
| AZE | 125,136 | 29,455 | 100% | <5 | 3.4 | 1.2 | 6.3 | 25.9 | 42 (39, 44) | $7,133 |
| BHS | 4,335 | 1,064 | 99% | <5 | 9.6 | 3.1 | 16.7 | 28.8 | 41 (38, 44) | $38,232 |
| BHR | 19,558 | 4,536 | 98% | <5 | 3.2 | 1.2 | 5.9 | 30.0 | 36 (33, 39) | $29,290 |
| BGD | 3,489,953 | 691,891 | 70% | 626 | 17.9 | 9.4 | 48.3 | 26.0 | 42 (38, 44) | $2,551 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| BRB | 3,155 | 774 | 98% | <5 | 4.4 | 1.5 | 7.7 | 27.7 | 44 (41, 47) | $23,804 |
| BLR | 65,050 | 14,180 | 100% | <5 | 0.1 | 0 | 0 | 28.7 | 42 (39, 45) | $7,897 |
| BEL | 101,686 | 22,088 | 100% | <5 | 0.4 | 0.2 | 0.8 | 31.0 | 43 (40, 46) | $54,690 |
| BLZ | 7,410 | 1,813 | 95% | <5 | 8.5 | 2.8 | 14.7 | 27.2 | 43 (40, 46) | $7,460 |
| BEN | 478,062 | 83,370 | 81% | 448 | 93.7 | 71.2 | 380.5 | 29.1 | 38 (36, 41) | $1,394 |
| BMU | 1,000 | 220 | 100% | <5 | 9.4 | 0 | 0 | 32.1 | 44 (41, 47) | $132,604 |
| BTN | 9,958 | 1,960 | 99% | <5 | 7.3 | 3.8 | 19.6 | 29.9 | 38 (36, 41) | $3,839 |
| BOL | 260,151 | 63,800 | 72% | 48 | 18.6 | 6.1 | 32.2 | 28.1 | 38 (35, 40) | $3,686 |
| BIH | 24,569 | 5,691 | 100% | <5 | 0.6 | 0.2 | 1.1 | 29.0 | 44 (40, 47) | $8,663 |
| BWA | 61,294 | 10,765 | 100% | 17 | 28 | 21.4 | 112.9 | 28.7 | 33 (30, 36) | $7,826 |
| BRA | 2,601,670 | 640,177 | 98% | 221 | 8.5 | 2.8 | 14.7 | 27.8 | 42 (39, 45) | $10,378 |
| BRN | 6,237 | 1,232 | 100% | <5 | 5.4 | 2.8 | 14.6 | 30.7 | 40 (38, 43) | $32,891 |
| BGR | 62,645 | 13,722 | 94% | <5 | 0.5 | 0.2 | 1.2 | 27.9 | 41 (38, 43) | $15,884 |
| BFA | 728,612 | 127,111 | 96% | 318 | 43.7 | 33.3 | 175.5 | 29.2 | 38 (35, 40) | $883 |
| BDI | 460,882 | 80,655 | 75% | 326 | 70.9 | 54 | 287.2 | 30.2 | 33 (31, 36) | $192 |
| KHM | 361,586 | 71,905 | 99% | 74 | 20.4 | 10.7 | 55.3 | 27.9 | 40 (38, 43) | $2,430 |
| CMR | 957,392 | 167,306 | 69% | 448 | 46.7 | 35.6 | 187.7 | 28.4 | 36 (33, 39) | $1,737 |
| CAN | 356,745 | 78,341 | 98% | <5 | 1.1 | 0.5 | 2.4 | 31.4 | 44 (40, 46) | $54,220 |
| CPV | 6,440 | 1,122 | 97% | <5 | 7.2 | 5.5 | 29.1 | 28.6 | 44 (41, 47) | $4,861 |
| CAF | 238,858 | 41,825 | 40% | 299 | 125.1 | 95.1 | 507.9 | 29.0 | 31 (28, 34) | $496 |
| TCD | 819,054 | 142,364 | 47% | 1,107 | 135.2 | 102.7 | 544.8 | 29.2 | 36 (33, 39) | $989 |
| CHL | 176,196 | 43,206 | 100% | <5 | 1.3 | 0.4 | 2.2 | 31.2 | 42 (38, 44) | $17,067 |

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|---|---|---|---|---|---|---|---|---|---|---|
| CHN | 8,899,881 | 2,253,138 | 100% | 215 | 2.4 | 0.8 | 3.8 | 29.0 | 47 (44, 50) | $12,951 |
| COL | 705,009 | 173,722 | 98% | 53 | 7.5 | 2.4 | 13.1 | 26.6 | 46 (43, 49) | $7,001 |
| COM | 24,366 | 4,270 | 97% | 8 | 32.3 | 24.5 | 131.8 | 30.2 | 35 (32, 37) | $1,682 |
| COG | 189,365 | 33,129 | 94% | 83 | 43.6 | 33.3 | 175.1 | 28.6 | 34 (31, 37) | $2,478 |
| CRI | 51,969 | 12,755 | 99% | <5 | 3.1 | 1 | 5.3 | 28.2 | 46 (43, 49) | $16,942 |
| CIV | 997,001 | 173,270 | 84% | 647 | 64.9 | 49.4 | 265.9 | 29.0 | 38 (35, 41) | $2,555 |
| HRV | 31,446 | 7,290 | 100% | <5 | 0.3 | 0 | 0 | 30.7 | 41 (38, 44) | $21,865 |
| CUB | 95,938 | 23,567 | 100% | <5 | 4.4 | 1.4 | 7.7 | 26.2 | 44 (41, 46) | $9,605 |
| CYP | 14,524 | 3,408 | 100% | <5 | 2.6 | 1 | 4.8 | 31.7 | 43 (40, 46) | $36,551 |
| CZE | 91,845 | 20,109 | 100% | <5 | 0.3 | 0.1 | 0.6 | 30.4 | 41 (38, 44) | $31,591 |
| COD | 4,369,683 | 763,027 | 85% | 3,375 | 77.2 | 58.8 | 311.7 | 30.1 | 32 (29, 35) | $633 |
| DNK | 57,810 | 12,115 | 96% | <5 | 0.3 | 0.2 | 0.8 | 31.6 | 43 (41, 46) | $68,454 |
| DJI | 23,946 | 4,202 | 87% | 7 | 29.3 | 22.3 | 119.4 | 31.5 | 33 (31, 36) | $3,398 |
| DMA | 1,000 | 246 | 100% | <5 | 14.1 | 4.6 | 24.4 | 28.2 | 42 (38, 44) | $9,913 |
| DOM | 203,183 | 50,003 | 99% | 32 | 15.8 | 5.2 | 27.4 | 27.4 | 44 (41, 47) | $10,630 |
| TLS | 30,561 | 6,075 | 69% | 9 | 28.6 | 15 | 77.8 | 29.4 | 41 (38, 43) | $1,503 |
| ECU | 270,300 | 66,295 | 96% | 19 | 7 | 2.3 | 12.2 | 27.4 | 44 (41, 46) | $6,738 |
| EGY | 2,405,717 | 554,369 | 97% | 78 | 3.3 | 1.2 | 6.2 | 28.0 | 38 (35, 40) | $3,457 |
| SLV | 99,428 | 24,560 | 98% | 5 | 5 | 1.6 | 8.6 | 27.1 | 44 (41, 46) | $5,365 |
| GNQ | 54,694 | 9,512 | 68% | 17 | 31.4 | 23.8 | 127.7 | 27.0 | 35 (31, 38) | $6,678 |
| ERI | 99,058 | 17,277 | 34% | 52 | 52.7 | 40 | 214 | 29.2 | 36 (33, 38) | $689 |
| EST | 11,036 | 2,312 | 99% | <5 | 0.9 | 0 | 0 | 31.0 | 42 (39, 44) | $30,133 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SWZ | 29,622 | 5,161 | 93% | 6 | 21.3 | 16.3 | 84.9 | 27.9 | 28 (26, 31) | $3,742 |
| ETH | 4,105,685 | 720,136 | 50% | 1,447 | 35.2 | 26.9 | 143 | 29.1 | 38 (36, 41) | $1,011 |
| FJI | 16,631 | 3,804 | 100% | <5 | 3.8 | 1.4 | 7.4 | 28.8 | 38 (35, 41) | $5,889 |
| FIN | 43,556 | 9,199 | 100% | <5 | 0.7 | 0.3 | 1.8 | 31.5 | 44 (41, 47) | $52,822 |
| FRA | 638,891 | 138,573 | 98% | 5 | 0.7 | 0.3 | 1.6 | 31.6 | 44 (41, 47) | $44,691 |
| GAB | 68,745 | 11,932 | 95% | 29 | 42.1 | 32.1 | 170.2 | 28.5 | 36 (33, 39) | $8,071 |
| GMB | 82,092 | 14,367 | 84% | 52 | 64.1 | 48.5 | 257.9 | 29.8 | 32 (29, 35) | $888 |
| GEO | 43,765 | 10,229 | 100% | <5 | 3.8 | 1.4 | 7 | 28.5 | 43 (40, 45) | $8,284 |
| DEU | 719,249 | 155,132 | 96% | <5 | 0.3 | 0.1 | 0.8 | 31.5 | 43 (39, 45) | $53,940 |
| GHA | 888,947 | 155,054 | 88% | 377 | 42.4 | 32.3 | 171.6 | 29.5 | 34 (31, 36) | $2,384 |
| GRC | 73,661 | 17,158 | 100% | <5 | 0.5 | 0.2 | 0.9 | 32.0 | 43 (40, 45) | $23,401 |
| GRL | 1,000 | 220 | 100% | <5 | 9.4 | 0 | 0 | 27.9 | 43 (39, 45) | $58,499 |
| GRD | 1,371 | 337 | 100% | <5 | 9.3 | 3 | 16 | 28.6 | 41 (37, 43) | $11,308 |
| GUM | 2,941 | 676 | 100% | <5 | 11.4 | 4.3 | 21.9 | 29.1 | 48 (45, 51) | $41,833 |
| GTM | 377,167 | 92,451 | 70% | 45 | 11.9 | 3.9 | 20.6 | 27.3 | 40 (37, 43) | $5,758 |
| GIN | 487,595 | 85,443 | 55% | 436 | 89.3 | 68.2 | 361.7 | 28.3 | 36 (33, 39) | $1,555 |
| GNB | 64,679 | 11,326 | 54% | 59 | 91.4 | 69.5 | 371.4 | 29.5 | 34 (31, 37) | $965 |
| GUY | 16,764 | 4,132 | 98% | <5 | 9.5 | 3.1 | 16.5 | 27.0 | 37 (33, 40) | $20,474 |
| HTI | 258,348 | 63,888 | 42% | 107 | 41.6 | 13.6 | 72 | 29.6 | 31 (28, 34) | $1,706 |
| HND | 233,793 | 57,221 | 94% | 14 | 5.9 | 1.9 | 10.3 | 27.2 | 39 (35, 41) | $3,227 |
| HUN | 85,373 | 18,577 | 100% | <5 | 1.1 | 0.5 | 2.4 | 30.0 | 39 (36, 42) | $22,312 |
| ISL | 4,347 | 914 | 97% | <5 | 2.2 | 0 | 0 | 30.8 | 45 (41, 47) | $79,960 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| IND | 23,219,488 | 4,563,814 | 89% | 2,912 | 12.5 | 6.5 | 33.8 | 27.5 | 39 (36, 42) | $2,530 |
| IDN | 4,482,359 | 892,744 | 97% | 937 | 20.9 | 11 | 56.6 | 29.0 | 41 (38, 44) | $4,876 |
| IRN | 1,173,463 | 230,828 | 99% | 29 | 2.5 | 1.3 | 6.6 | 28.8 | 42 (39, 45) | $4,466 |
| IRQ | 1,159,682 | 271,686 | 96% | 147 | 12.7 | 4.6 | 23.4 | 28.6 | 40 (36, 43) | $5,965 |
| IRL | 53,268 | 11,221 | 100% | <5 | 0.4 | 0.2 | 0.9 | 32.7 | 44 (41, 46) | $103,888 |
| ISR | 172,312 | 40,215 | 100% | <5 | 0.5 | 0.2 | 0.9 | 30.9 | 45 (41, 47) | $52,004 |
| ITA | 384,627 | 88,912 | 99% | <5 | 0.6 | 0.2 | 1.2 | 32.3 | 44 (41, 47) | $39,065 |
| JAM | 33,007 | 8,156 | 100% | 5 | 16.5 | 5.4 | 28.6 | 27.9 | 43 (40, 46) | $6,840 |
| JPN | 749,884 | 189,296 | 100% | <5 | 0.5 | 0.1 | 0.7 | 31.9 | 48 (44, 50) | $33,836 |
| JOR | 235,776 | 55,156 | 100% | 14 | 5.9 | 2.1 | 10.9 | 29.8 | 38 (35, 41) | $4,466 |
| KAZ | 409,417 | 75,651 | 100% | 7 | 1.5 | 0.9 | 4.9 | 29.0 | 41 (38, 43) | $12,879 |
| KEN | 1,499,998 | 261,827 | 89% | 1,028 | 68.5 | 52.1 | 278.4 | 28.2 | 37 (34, 40) | $1,952 |
| KIR | 3,421 | 778 | 92% | <5 | 10.1 | 3.8 | 19.4 | 29.1 | 37 (35, 40) | $2,178 |
| KWT | 49,342 | 11,556 | 99% | <5 | 1.5 | 0.5 | 2.7 | 30.3 | 43 (40, 47) | $34,076 |
| KGZ | 150,759 | 27,923 | 100% | 10 | 6.5 | 4.1 | 21.6 | 28.5 | 44 (41, 46) | $2,138 |
| LAO | 163,043 | 32,378 | 80% | 27 | 16.6 | 8.8 | 45.2 | 26.3 | 41 (38, 44) | $2,067 |
| LVA | 14,250 | 2,991 | 98% | <5 | 1.8 | 0.8 | 4.3 | 30.3 | 39 (37, 42) | $22,676 |
| LBN | 93,205 | 21,725 | 98% | <5 | 2.9 | 1 | 5.3 | 29.2 | 43 (39, 46) | $3,478 |
| LSO | 55,728 | 9,790 | 89% | 48 | 86.4 | 65.9 | 349.1 | 27.9 | 26 (24, 29) | $916 |
| LBR | 170,065 | 29,537 | 84% | 193 | 113.5 | 86 | 457 | 28.3 | 35 (32, 39) | $799 |
| LBY | 124,371 | 28,690 | 100% | 14 | 11.4 | 4.2 | 21.6 | 31.9 | 36 (33, 39) | $6,173 |
| LTU | 21,434 | 4,519 | 100% | <5 | 0.7 | 0.3 | 1.8 | 30.3 | 40 (37, 42) | $27,786 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| LUX | 6,946 | 1,503 | 100% | <5 | 1.4 | 0 | 0 | 32.3 | 44 (41, 47) | $131,408 |
| MDG | 1,001,244 | 174,890 | 46% | 807 | 80.5 | 61.4 | 326.2 | 27.9 | 36 (33, 39) | $509 |
| MWI | 662,289 | 115,116 | 96% | 269 | 40.7 | 30.9 | 164.4 | 27.7 | 34 (31, 37) | $602 |
| MYS | 435,989 | 86,213 | 100% | 18 | 3.9 | 2.1 | 10.6 | 31.0 | 38 (36, 40) | $11,379 |
| MDV | 5,795 | 1,147 | 100% | <5 | 5 | 2.6 | 13.3 | 30.2 | 43 (40, 45) | $12,530 |
| MLI | 951,445 | 165,934 | 66% | 632 | 66.4 | 50.4 | 270 | 28.9 | 36 (33, 38) | $1,036 |
| MLT | 4,213 | 974 | 100% | <5 | 2.2 | 0 | 0 | 30.9 | 44 (41, 46) | $40,182 |
| MHL | 1,000 | 228 | 92% | <5 | 12.7 | 4 | 23.9 | 27.1 | 36 (33, 39) | $6,678 |
| MRT | 172,885 | 30,132 | 70% | 120 | 68.9 | 52.5 | 278.3 | 30.2 | 35 (33, 38) | $2,121 |
| MUS | 11,804 | 2,068 | 100% | <5 | 11.9 | 9.1 | 47.6 | 29.1 | 43 (40, 46) | $11,182 |
| MEX | 2,037,689 | 498,305 | 88% | 109 | 5.3 | 1.8 | 9.2 | 26.8 | 41 (38, 44) | $13,826 |
| FSM | 2,512 | 573 | 100% | <5 | 16.3 | 6.1 | 31.3 | 28.9 | 38 (35, 41) | $3,941 |
| MDA | 32,986 | 7,173 | 100% | <5 | 1.8 | 0.8 | 3.9 | 28.0 | 43 (40, 45) | $6,800 |
| MCO | 1,000 | 217 | 100% | <5 | 9.4 | 0 | 0 | 30.9 | 42 (39, 45) | $256,581 |
| MNG | 65,019 | 16,428 | 100% | <5 | 6 | 1.9 | 9.6 | 29.3 | 42 (39, 45) | $5,839 |
| MNE | 6,981 | 1,625 | 99% | <5 | 1.3 | 0 | 0 | 30.2 | 38 (35, 40) | $12,077 |
| MAR | 629,832 | 145,791 | 87% | 84 | 13.4 | 5 | 25.3 | 29.9 | 36 (33, 38) | $3,771 |
| MOZ | 1,260,855 | 221,696 | 68% | 187 | 14.9 | 11.3 | 60.4 | 28.4 | 32 (29, 35) | $623 |
| MMR | 903,822 | 180,317 | 60% | 249 | 27.4 | 14.5 | 74.2 | 28.8 | 41 (38, 44) | $1,233 |
| NAM | 76,715 | 13,475 | 88% | 20 | 25.1 | 19.1 | 102.4 | 28.9 | 34 (32, 37) | $4,188 |
| NRU | 1,000 | 228 | 98% | <5 | 12.7 | 3.9 | 24.2 | 27.1 | 36 (33, 39) | $12,754 |
| NPL | 574,297 | 112,087 | 80% | 127 | 22.1 | 11.5 | 59.8 | 25.3 | 39 (36, 41) | $1,382 |

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|---|---|---|---|---|---|---|---|---|---|---|
| NLD | 167,842 | 36,304 | 100% | <5 | 0.4 | 0.2 | 0.9 | 31.8 | 43 (40, 46) | $64,572 |
| NZL | 59,236 | 13,736 | 96% | <5 | 0.7 | 0.3 | 1.3 | 30.6 | 43 (40, 46) | $48,655 |
| NIC | 132,214 | 32,396 | 94% | 10 | 7.7 | 2.5 | 13.3 | 26.0 | 43 (40, 46) | $2,609 |
| NER | 1,095,892 | 191,240 | 44% | 694 | 63.3 | 48.1 | 259.2 | 29.1 | 38 (35, 40) | $638 |
| NGA | 7,509,758 | 1,314,364 | 51% | 13,484 | 179.5 | 137.3 | 721.2 | 29.2 | 39 (36, 41) | $1,597 |
| MKD | 16,878 | 3,900 | 100% | <5 | 0.6 | 0 | 0 | 29.0 | 41 (38, 43) | $8,624 |
| MNP | 1,000 | 228 | 100% | <5 | 12.7 | 4 | 24 | 29.1 | 42 (40, 45) | $23,786 |
| NOR | 51,545 | 10,830 | 99% | <5 | 0.2 | 0 | 0 | 31.6 | 44 (41, 47) | $87,497 |
| OMN | 85,065 | 19,843 | 100% | <5 | 2.4 | 0.9 | 4.4 | 31.7 | 38 (35, 40) | $20,972 |
| PAK | 6,882,058 | 1,355,041 | 68% | 1,662 | 24.1 | 12.6 | 65.3 | 28.9 | 37 (35, 40) | $1,365 |
| PLW | 1,000 | 228 | 99% | <5 | 12.7 | 3.9 | 24.2 | 28.5 | 40 (37, 42) | $15,899 |
| PSE | 146,384 | 33,941 | 100% | <5 | 3.1 | 1.1 | 5.7 | 28.6 | 42 (38, 44) | $3,455 |
| PAN | 71,469 | 17,573 | 93% | <5 | 4.7 | 1.5 | 8.1 | 27.3 | 47 (43, 50) | $18,686 |
| PNG | 255,331 | 58,117 | 56% | 62 | 23.9 | 9 | 45.9 | 29.3 | 37 (34, 40) | $2,966 |
| PRY | 136,778 | 33,745 | 91% | 10 | 7.4 | 2.4 | 12.8 | 27.7 | 42 (39, 45) | $6,300 |
| PER | 539,623 | 132,090 | 95% | 35 | 6.5 | 2.1 | 11.3 | 28.8 | 43 (40, 45) | $7,888 |
| PHL | 1,840,477 | 368,064 | 90% | 229 | 12.4 | 6.5 | 34.1 | 29.0 | 41 (38, 43) | $3,804 |
| POL | 317,916 | 69,612 | 100% | <5 | 0.1 | 0.1 | 0.3 | 29.9 | 41 (38, 43) | $22,145 |
| PRT | 86,646 | 20,096 | 97% | <5 | 1.4 | 0.5 | 2.7 | 31.7 | 44 (40, 46) | $27,386 |
| PRI | 18,851 | 4,642 | 100% | <5 | 1.4 | 0.5 | 2.4 | 27.8 | 49 (45, 52) | $36,948 |
| QAT | 29,516 | 6,912 | 100% | <5 | 0.8 | 0.3 | 1.4 | 30.4 | 38 (35, 41) | $80,196 |
| ROU | 183,623 | 39,875 | 98% | <5 | 1.1 | 0.5 | 2.5 | 28.1 | 43 (41, 46) | $18,404 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| RUS | 1,297,207 | 282,962 | 100% | 12 | 0.9 | 0.4 | 2 | 28.9 | 41 (38, 43) | $14,159 |
| RWA | 395,578 | 68,809 | 94% | 164 | 41.5 | 31.5 | 169 | 30.6 | 34 (31, 36) | $1,027 |
| KNA | 1,000 | 246 | 100% | <5 | 12.7 | 4.2 | 22 | 27.6 | 43 (40, 45) | $22,600 |
| LCA | 2,019 | 498 | 100% | <5 | 6.3 | 2 | 10.9 | 28.8 | 43 (39, 46) | $13,555 |
| VCT | 1,232 | 305 | 99% | <5 | 10.3 | 3.4 | 17.8 | 28.2 | 42 (39, 45) | $10,582 |
| WSM | 5,503 | 1,262 | 89% | <5 | 12.9 | 4.8 | 24.7 | 29.3 | 40 (37, 43) | $4,330 |
| SMR | 1,000 | 232 | 100% | <5 | 9.4 | 0 | 0 | 32.8 | 46 (42, 50) | $54,265 |
| STP | 6,507 | 1,130 | 97% | <5 | 13.6 | 10.3 | 55.3 | 28.5 | 40 (37, 43) | $2,941 |
| SAU | 546,038 | 127,098 | 100% | 8 | 1.4 | 0.5 | 2.6 | 30.1 | 36 (33, 39) | $36,157 |
| SEN | 531,890 | 93,225 | 94% | 228 | 42.9 | 32.6 | 174.8 | 29.9 | 34 (31, 37) | $1,698 |
| SRB | 59,840 | 13,829 | 100% | <5 | 1 | 0.4 | 2 | 29.5 | 39 (36, 41) | $12,282 |
| SYC | 1,744 | 304 | 100% | <5 | 10.4 | 7.9 | 41.9 | 27.6 | 44 (41, 46) | $18,263 |
| SLE | 258,903 | 45,758 | 87% | 165 | 63.9 | 48.7 | 255.2 | 28.6 | 37 (34, 39) | $758 |
| SGP | 47,472 | 9,454 | 100% | <5 | 0.9 | 0.5 | 2.5 | 32.3 | 48 (45, 51) | $85,412 |
| SVK | 52,271 | 11,457 | 97% | <5 | 0.4 | 0.2 | 0.9 | 28.9 | 44 (41, 47) | $24,674 |
| SVN | 17,902 | 4,171 | 100% | <5 | 0.5 | 0 | 0 | 30.4 | 43 (40, 46) | $32,610 |
| SLB | 21,548 | 4,910 | 86% | <5 | 15.6 | 5.9 | 29.9 | 29.2 | 38 (35, 40) | $2,076 |
| SOM | 788,763 | 137,567 | 32% | 803 | 101.7 | 77.6 | 409.5 | 29.4 | 32 (29, 35) | $597 |
| ZAF | 1,186,793 | 207,106 | 97% | 252 | 21.3 | 16.2 | 85.8 | 28.3 | 34 (31, 36) | $6,023 |
| KOR | 236,394 | 59,993 | 100% | <5 | 0.6 | 0.2 | 0.9 | 33.4 | 46 (43, 49) | $33,121 |
| SSD | 328,308 | 57,441 | 40% | 410 | 125.1 | 95.2 | 501 | 28.6 | 35 (31, 38) | $1,080 |
| ESP | 336,821 | 77,569 | 100% | <5 | 0.3 | 0.1 | 0.5 | 32.5 | 45 (42, 48) | $33,509 |

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|---|---|---|---|---|---|---|---|---|---|---|
| LKA | 324,102 | 63,606 | 100% | 9 | 2.9 | 1.5 | 7.7 | 29.6 | 41 (37, 44) | $3,799 |
| SDN | 1,682,049 | 388,149 | 78% | 823 | 49.1 | 18.2 | 92.4 | 29.8 | 35 (32, 38) | $797 |
| SUR | 10,879 | 2,680 | 100% | <5 | 10.6 | 3.4 | 18.4 | 28.4 | 42 (38, 45) | $5,494 |
| SWE | 97,915 | 20,484 | 100% | <5 | 0.4 | 0.2 | 0.9 | 31.6 | 44 (41, 47) | $55,567 |
| CHE | 83,702 | 18,176 | 100% | <5 | 0.5 | 0.2 | 1.2 | 32.3 | 45 (42, 48) | $100,632 |
| SYR | 521,601 | 121,537 | 96% | 20 | 3.9 | 1.4 | 7.2 | 28.8 | 41 (38, 44) | $847 |
| TJK | 271,420 | 49,542 | 98% | 5 | 2.2 | 1.4 | 7.1 | 26.5 | 41 (39, 44) | $1,178 |
| TZA | 2,346,391 | 411,733 | 85% | 1,171 | 49.9 | 38 | 203 | 28.9 | 37 (34, 40) | $1,224 |
| THA | 591,200 | 117,748 | 100% | 30 | 5.1 | 2.7 | 13.9 | 28.3 | 46 (43, 49) | $7,195 |
| TGO | 289,759 | 50,431 | 69% | 182 | 63.1 | 47.9 | 256.8 | 29.1 | 38 (35, 40) | $986 |
| TON | 2,418 | 552 | 98% | <5 | 8.5 | 3.2 | 16.2 | 29.9 | 38 (35, 41) | $4,864 |
| TTO | 16,094 | 3,986 | 99% | <5 | 6.9 | 2.2 | 11.9 | 27.8 | 42 (38, 45) | $18,639 |
| TUN | 167,729 | 38,759 | 98% | 11 | 6.9 | 2.5 | 12.9 | 31.3 | 38 (34, 41) | $3,950 |
| TUR | 1,072,014 | 250,813 | 97% | 30 | 2.8 | 1 | 5.2 | 29.2 | 44 (40, 46) | $13,106 |
| TKM | 160,100 | 29,505 | 100% | <5 | 0.7 | 0.4 | 2.3 | 27.8 | 41 (38, 43) | $8,233 |
| TUV | 1,000 | 229 | 100% | <5 | 12.7 | 3.9 | 24.2 | 29.2 | 39 (36, 42) | $6,345 |
| UGA | 1,712,750 | 296,676 | 88% | 528 | 30.8 | 23.5 | 125.2 | 28.3 | 37 (34, 40) | $1,002 |
| UKR | 212,231 | 46,280 | 100% | <5 | 1.4 | 0.6 | 3.1 | 28.1 | 42 (38, 45) | $5,140 |
| ARE | 104,015 | 24,318 | 100% | <5 | 0.5 | 0.2 | 0.9 | 31.9 | 34 (32, 36) | $49,041 |
| GBR | 688,388 | 144,501 | 100% | 5 | 0.8 | 0.4 | 1.9 | 30.9 | 42 (39, 45) | $49,201 |
| USA | 3,657,476 | 800,615 | 99% | 57 | 1.6 | 0.7 | 3.4 | 29.9 | 39 (36, 42) | $82,305 |
| VIR | 1,000 | 246 | 100% | <5 | 18.3 | 6 | 31.6 | 27.7 | 47 (43, 50) | $44,321 |

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|---|---|---|---|---|---|---|---|---|---|---|
| URY | 33,443 | 8,217 | 100% | <5 | 1.9 | 0.6 | 3.4 | 29.2 | 45 (42, 47) | $23,019 |
| UZB | 943,547 | 172,514 | 99% | 39 | 4.1 | 2.6 | 13.5 | 27.0 | 43 (40, 45) | $2,879 |
| VUT | 8,988 | 2,058 | 91% | <5 | 12.7 | 4.8 | 24.3 | 28.1 | 39 (36, 41) | $3,515 |
| VEN | 426,984 | 105,209 | 99% | 123 | 28.8 | 9.3 | 49.8 | 26.3 | 42 (39, 45) | $15,944 |
| VNM | 1,387,961 | 274,423 | 98% | 99 | 7.1 | 3.7 | 19.2 | 27.2 | 46 (43, 48) | $4,323 |
| YEM | 1,386,914 | 325,041 | 61% | 314 | 22.7 | 8.2 | 42 | 29.7 | 34 (31, 36) | $426 |
| ZMB | 685,565 | 119,818 | 94% | 106 | 15.5 | 11.8 | 62.2 | 28.4 | 33 (30, 36) | $1,331 |
| ZWE | 496,917 | 86,926 | 86% | 321 | 64.7 | 49.2 | 263.1 | 28.1 | 31 (28, 33) | $2,156 |

Country-specific parameters used to estimate the economic burden of postpartum haemorrhage (PPH). Country ISO3 codes were used for parameter estimation at country-level. Country-specific PPH counts, deaths and MMR were drawn from posterior estimates in the stage 2 Bayesian hierarchical model (section 2.2).

## Consequences of postpartum haemorrhage: a systematic review

### Search strategy and selection criteria

Population-based cohort studies (i.e., multi-country, national, regional or multi-centre studies) that reported complications or consequences of PPH in women following birth and where a PPH diagnosis was made were included. Cross-sectional studies with appropriate sampling techniques were also eligible. Large cluster randomised trials were eligible if the target sample included an unselected population. The age range and race of the participating women were unrestricted. Unpublished papers, preprints, editorials, comments, letters, case-reports, books, comments, editorials, and non-human studies and reviews were excluded.

### Databases searched

Five electronic databases were searched including MEDLINE, Web of Science, Embase, Cochrane Library, and Google Scholar using search strings for studies that reported consequences of PPH. The search strategy used the keyword 'postpartum haemorrhage' in the title and abstract and as a MeSH term to identify eligible studies using the advanced and expert search strategies (Table S10). Last search was conducted in July 2025. Duplicate studies were excluded by using automated and manual hand-search screening.

Grey literature was identified using Google Scholar. The reference lists of the final included studies and other searched reviews were checked to identify further eligible studies.

Table S10 Search strategies

| **Database** | **Search strings** |
|---|---|
| MEDLINE | (postpartum haemorrhage[Title/Abstract] OR postpartum hemorrhage[Title/Abstract] OR post-partum haemorrhage[Title/Abstract] OR post-partum hemorrhage[Title/Abstract] OR postpartum bleeding[TitleAbstract] OR post-partum bleeding[Title/Abstract]) AND (consequences*[Title/Abstract] OR complications*[Title/Abstract] OR deaths*[Title/Abstract] OR morbidity*[Title/Abstract] OR near miss*[Title/Abstract] OR near-miss*[Title/Abstract] OR outcome*[Title/Abstract] OR transfusion*[Title/Abstract])) |

| | |
|---|---|
| Web of Science | TS=(("postpartum hemorrhage" OR "postpartum haemorrhage" OR "post partum haemorrhage" OR "post partum haemorrhage") AND ("consequences" OR "complications" OR "deaths" OR "morbidity" OR "near miss" OR "near-miss" OR "outcome" OR "transfusion")) |
| Embase | (postpartum haemorrhage* OR postpartum haemorrhage* OR post partum haemorrhage* OR post partum haemorrhage*) AND (consequences OR complications OR deaths OR morbidity OR near miss* OR near-miss OR outcome OR transfusion) |
| Google Scholar | allintitle:("postpartum hemorrhage" OR "postpartum haemorrhage" OR "post partum hemorrhage" OR "post partum haemorrhage") AND (“consequences” OR “complications” OR “deaths” OR “morbidity” OR “near miss” OR “near-miss” OR “outcome” OR “transfusion”) |
| Cochrane Library | (("postpartum hemorrhage" OR "postpartum haemorrhage" OR "post partum hemorrhage" OR "post partum haemorrhage")):ti |

**Data extraction**

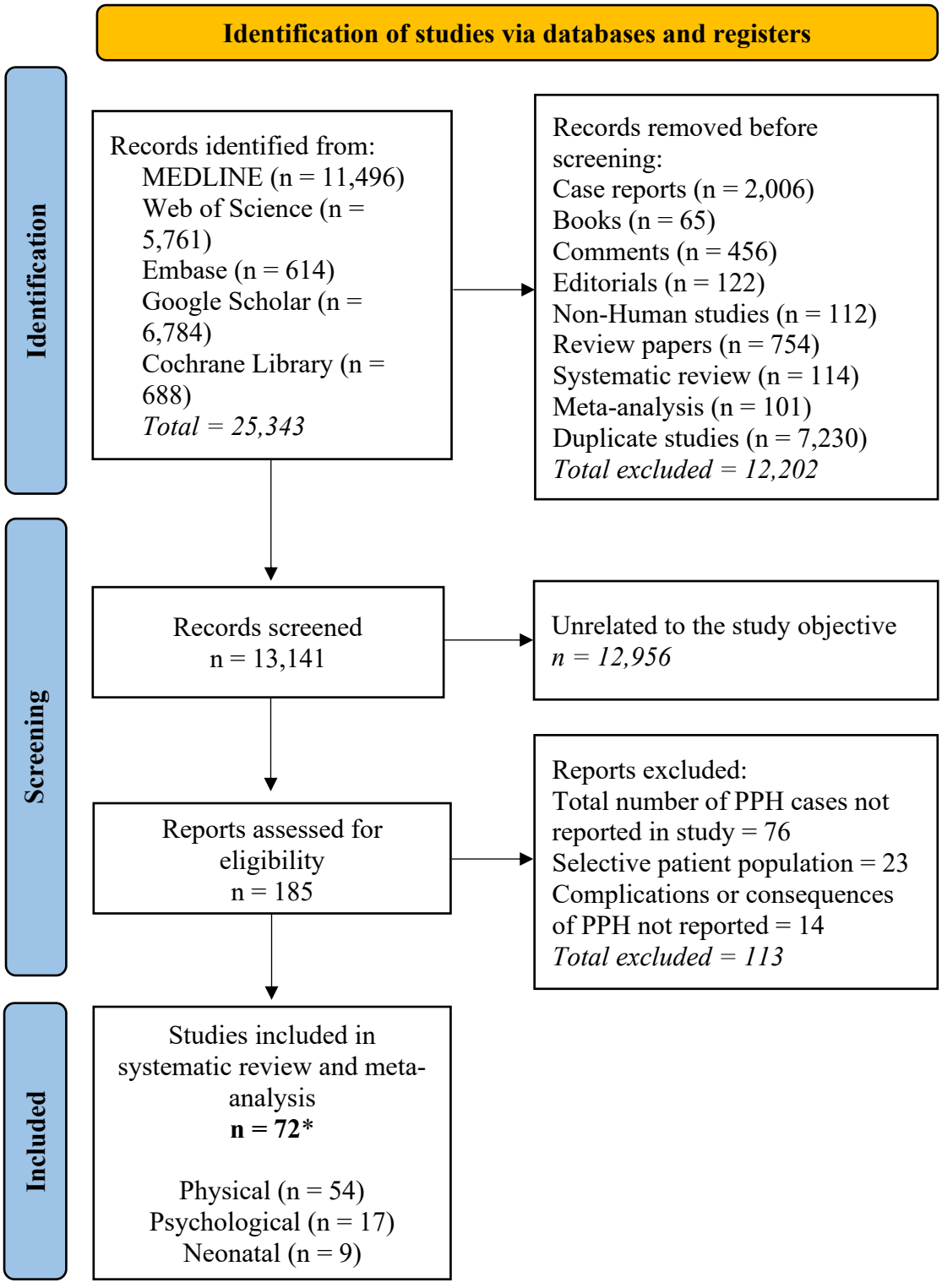
Two authors (K.N.S. and N.P.) independently screened studies. Initially by title and abstract, followed by full-text review if appropriate to determine inclusion eligibility. Any differences over inclusion were resolved by consensus following discussion with senior authors (A.C.).

Data extraction from the final selection of studies was undertaken independently by K.N.S. and N.P. and then cross-checked. When duplicate data from the same source population was found, the older study data was removed. The following data and information were extracted from each eligible study using a data extraction table: first author's last name and publication year, country, study design, study duration, number of women with PPH, number of physical, psychological and neonatal consequences or complications reported, and definition of PPH used.

The number of consequences and complications were grouped into the following categories: physical, psychological, and neonatal. STATA version 18 was used to estimate pooled rates of complications or consequences using a random-effects model. This review followed PRISMA reporting guidelines and is registered with PROSPERO, CRD42024520980.

A total of 13,141 studies were screened to include 72 studies (Figure S10) involving 8,417,625 events of PPH in women from 57 countries. There was a total of 240,430 consequences related to PPH. Rates of the consequences and complications due to PPH were pooled using a random-effects model (Figure S11). Quality of the included studies was assessed using the JBI Critical Appraisal Checklist tool (Tables S11, S12 and S13).

The methodological quality of included studies was evaluated by applying the Joanna Briggs Institute (JBI) critical appraisal tool for cohort studies, case-control, cross-sectional and controlled trials for the corresponding studies. The studies were classified as high quality (low risk of bias: >70%), moderate quality (moderate risk of bias: 50-70%), or low quality (high risk of bias: <50%). Of the 72 studies included in the review, all except two studies were of low risk of bias (Tables S11, S12, S13).




* Some of the included studies had data for more than one consequence domain: physical, psychological and neonatal

Figure S10: Study selection

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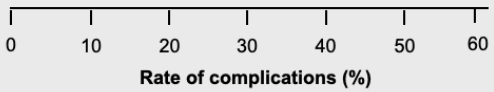
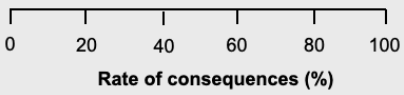
| | Number of studies analysed | Number of complications | Number of PPH | OR/RR/HR (95% CI) | Pooled rate (95% CI) |
|---|---|---|---|---|---|
| **Physical complications** | | | | | |
| Anaemia[70-74] | 5 | 1,504 | 3,408 | - | 46·3 (30·8, 62·1) |
| Blood transfusion[4,12,70,73-95] | 26 | 98,293 | 869,027 | - | 12·3 (9·9, 15·0) |
| Cardiac complications[80,82,89,92,96-101] | 10 | 5,969 | 921,902 | aHR: 1·96 (1·51, 2·53); 2 studies | 1·7 (0·4, 3·8) |
| Cerebral complications[82,96,98] | 3 | 97 | 35,869 | - | 0·5 (0·0, 2·0) |
| Coagulopathy[71-73,76,82,86,89,98,102] | 9 | 37,222 | 618,266 | - | 3·4 (1·4, 6·3) |
| Death[4,12,43,70-72,76,78,84-86,89,91,93,94,96,98,101,103-111] | 27 | 1,097 | 468,485 | cOR: 5·6 (3·75, 8·37); 1 study | 1·6 (0·8, 2·6) |
| Hepatic complications[96] | 1 | 30 | 9,985 | - | 0·3 (0·2, 0·4) |
| Hysterectomy[4,12,70-73,76,78,82, 89,91,93,94,96,101,104,106,108,112-115] | 28 | 12,800 | 741,641 | - | 2·1 (1·3, 3·1) |
| ICU admission[4,43,76,78,82,84,86,89,90,93,94,98,116] | 13 | 2,256 | 688,728 | - | 3·3 (1·0, 6·7) |
| Multiple organ failure[86] | 1 | 2 | 124 | - | 1·6 (0·03, 4·8) |
| Near miss[86,109] | 2 | 283 | 2,211 | - | 18·0 (6·6, 33·3) |
| Pulmonary embolism[82,89,96] | 3 | 896 | 589,720 | - | 0·3 (0·1, 0·6) |
| Prolonged hospitalisation[43,76,89] | 3 | 14,089 | 596,652 | - | 13·1 (0·0, 51·0) |
| Readmission[117] | 1 | 10,618 | 454,276 | - | 2·3 (2·3, 2·4) |
| Renal complications[72,76,82,86,89,96,98,101] | 8 | 3,366 | 617,035 | - | 1·0 (0·5, 1·7) |
| Respiratory complications[76,82,86,89,96,98,101] | 7 | 3,125 | 615,943 | - | 2·2 (0·7, 4·7) |
| Seizures[96] | 1 | 43 | 9,985 | - | 0·4 (0·3, 0·6) |
| Sepsis[76,82,89,118] | 4 | 1,953 | 625,407 | - | 0·6 (0·1, 1·6) |
| Sheehan's syndrome[98] | 1 | 3 | 230 | - | 1·3 (0·2, 3·3) |
| Shock[82,101] | 2 | 173 | 10,864 | - | 2·9 (0·3, 7·5) |



**B**

| | Number of studies analysed | Number of consequences | Number of PPH | OR/RR/HR (95% CI) | Pooled rate (95% CI) |
|---|---|---|---|---|---|
| **Postpartum psychological consequences** | | | | | |
| Anxiety[119,120] | 2 | 808 | 13,049 | aHR: 0·99 (0·90, 1·09), 1 study | 28·5 (0·0, 88·3) |
| Depression[96,102,119-130] | 14 | 2,026 | 55,942 | aHR: 1·08 (0·99, 1·17), 3 studies | 15·5 (8·5, 24·2) |
| Flashbacks/negative memories[122,131] | 2 | 57 | 89 | - | 62·8 (48·2, 76·4) |
| Insufficient sleep[121] | 1 | 78 | 196 | aHR: 1·81 (0·91, 3·57), 1 study | 39·8 (33·0, 46·8) |
| Nightmares[122] | 1 | 6 | 21 | - | 28·6 (10·9, 50·0) |
| PTSD[100,119,123,125,126,128,132,133] | 8 | 282 | 15,965 | aHR: 1·17 (0·73, 1·89), 1 study | 10·7 (3·1, 21·7) |
| Severe mental illness[120,125] | 2 | 34 | 14,213 | aHR: 0·65 (0·4, 1·08), 1 study | 2·5 (0·0, 16·1) |
| **Neonatal consequences** | | | | | |
| Inability to exclusively breastfeed[79,81,121,130,134] | 5 | 28,649 | 122,726 | aOR: 0·88 (0·86, 0·90), 1 study* | 27·8 (19·3, 37·2) |
| NICU admission[43,71,79,81,135] | 5 | 8,292 | 57,522 | - | 16·1 (11·9, 20·8) |
| Pre-discharge neonatal death[43,136] | 2 | 834 | 21,312 | - | 9·6 (0·0, 41·7) |



C

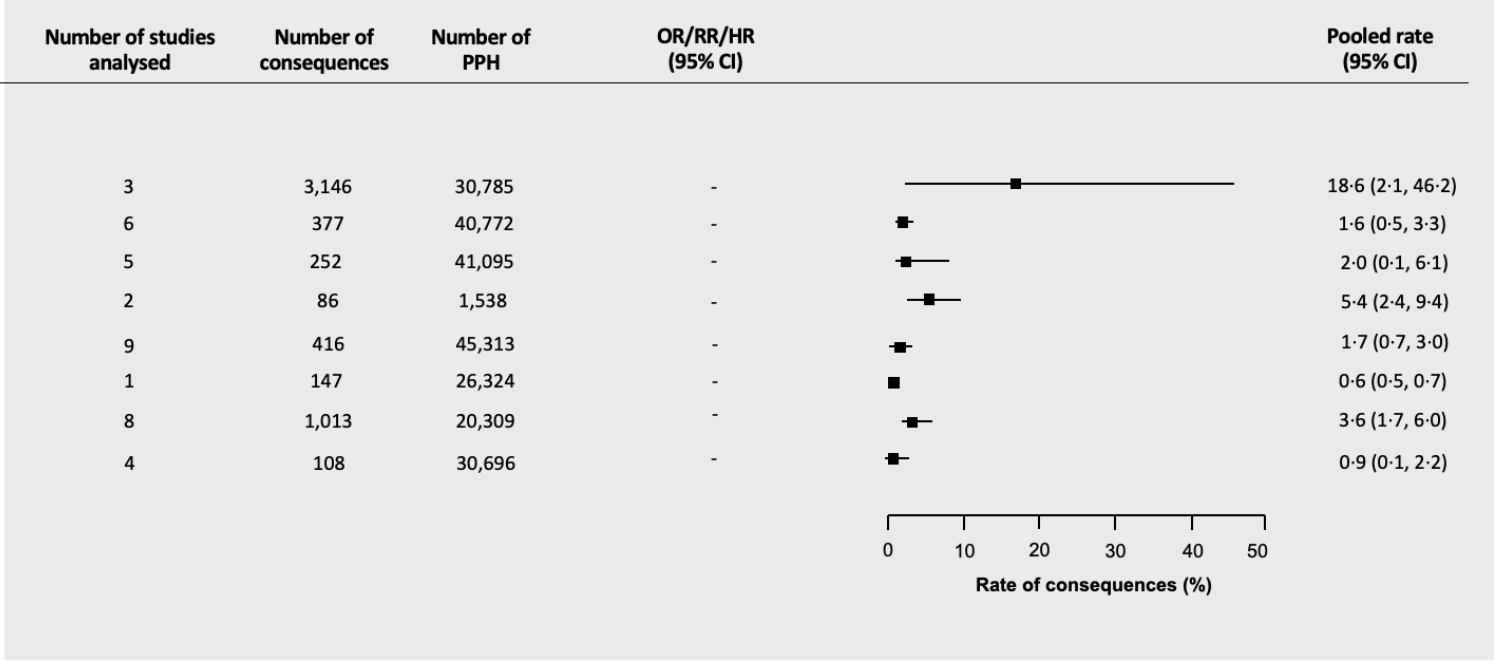



Figure S11. Rate of physical complications (A), psychological and neonatal (B), and other treatment consequences (C) related to postpartum haemorrhage

ICU: intensive care unit; HR: hazard ratio; NASG: non-pneumatic anti-shock garment; NICU: neonatal Intensive Care Unit; OR: odds ratio; PPH: postpartum haemorrhage; PTSD: post-traumatic stress disorder; RR: relative risk

*Women with PPH were less likely to be exclusively breastfeeding their babies compared to those without PPH

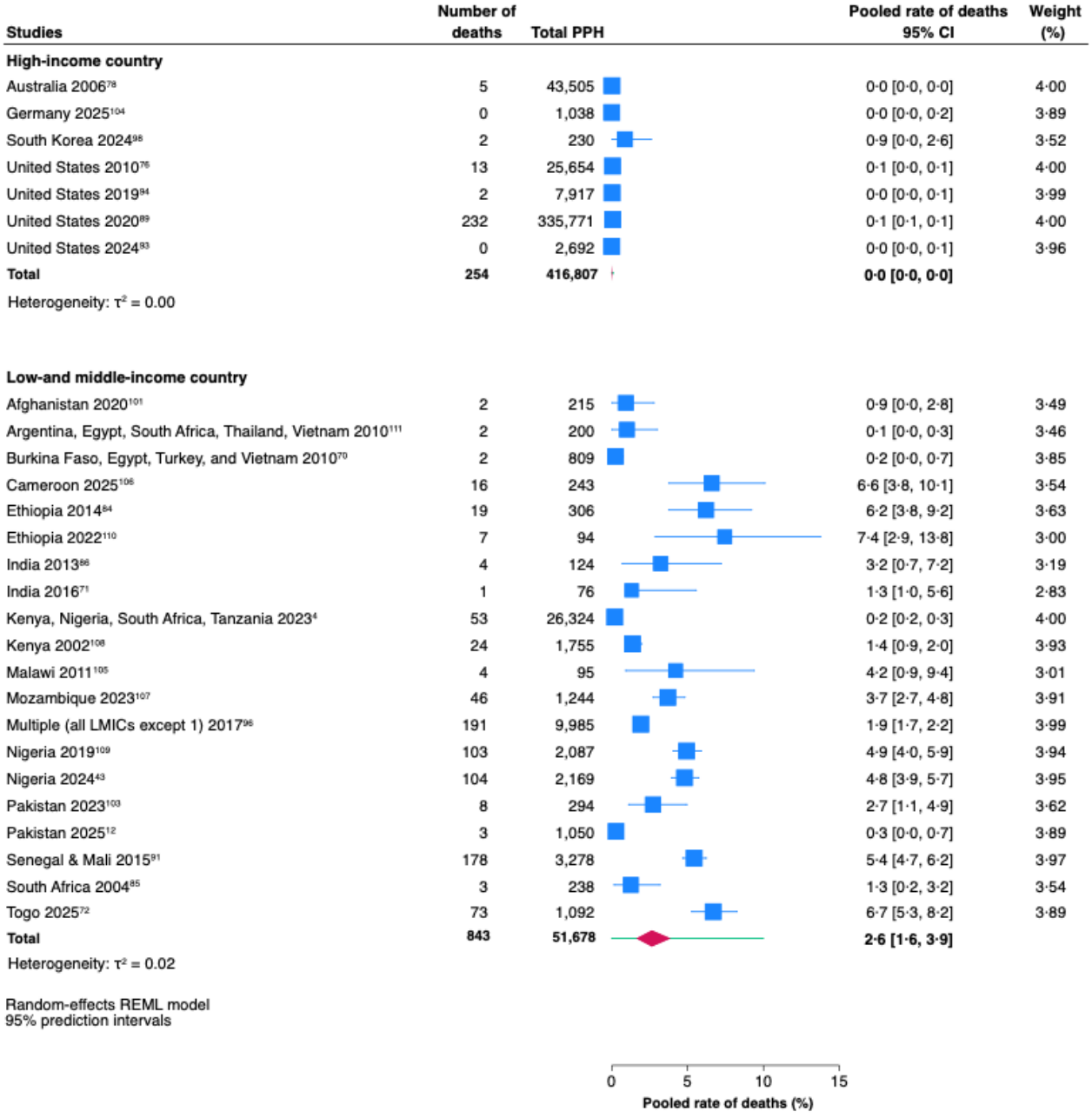



Figure S12: Maternal deaths from PPH: high income country versus low- and middle-income country

Maternal deaths from PPH:

High income country (HIC) = 0.01% (95% CI: 0.00% to 0.03%)

Low- and middle-income country (LMIC) = 2.6 % (95% CI: 1.6% to 3.9%)

**Summary of references for Figure S11**

Anemia[70-74]

Blood tranfusion[4,12,70,73-95]

Cardiac complications[80,82,89,92,96-101]

Cerebral complications[82,96,98]

Coagulopathy[71-73,76,82,86,89,98,102]

Death[4,12,43,70-72,76,78,84-86,89,91,93,94,96,98,101,103-111]

Hepatic complications[96]

Hysterectomy[4,12,70-73,76,78,82-89,91,93,94,96,101,104,106,108,112-115]

ICU admission[4,43,76,78,82,84,86,89,90,93,94,98,116]

Multiple organ failure[86]

Near miss[86,109]

Pulmonary embolism[82,89,96]

Prolonged hospitalisation[43,76,89]

Readmission[117]

Renal complications[72,76,82,86,89,96,98,101]

Respiratory complications[76,82,86,89,96,98,101]

Seizure[96]

Sepsis[76,82,89,118]

Sheehan's syndrome[98]

Shock[82,101]

Anxiety[119,120]

Depression[96,102,119-130]

Flashbacks, neg memories[122,131]

Insufficient sleep[121]

Nightmares[122]

PTSD[100,119,123,125,126,128,132,133]

Severe mental illness[120,125]

Inability to exclusively breastfeed[79,81,121,130,134]

NICU admission[43,71,79,81,135]

Pre-discharge neonatal death[43,136]

Bimanual compression[70,87,108]

Compression suture[71,72,83,87,96,104]

Embolization[73,83,87,96,137]

Examination under anaesthesis[70,83]

Major vessel ligation[72,86,87,96,101,108,112,113,138]

NASG[4]

Tamponade[71,74,83,93,96,104,108,112]

Transfer to higher centre[4,12,74,91]

| Table S11. Quality assessment of the cohort studies | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Study ID** | **JBI Critical Appraisal Checklist for Cohort Studies** | | | | | | | | | | |
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **Total (%)** |
| **1.** | Anwar 2023 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **2.** | Balki 2008 | Y | Y | Y | UC | UC | Y | Y | Y | Y | N | Y | 72.7 |
| **3.** | Balki 2017 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **4.** | Barth 2025 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **5.** | Bateman 2010 | Y | Y | Y | N | N | Y | Y | Y | Y | N | Y | 72.7 |
| **6.** | Beltman 2011 | Y | Y | Y | UC | UC | Y | Y | Y | Y | N | Y | 72.7 |
| **7.** | Bonnet 2013 | Y | Y | Y | UC | UC | Y | Y | Y | Y | Y | Y | 81.8 |
| **8.** | Cameron 2006 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **9.** | Chessman 2018 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **10.** | Cho 2021 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **11.** | Deniau 2024 | Y | Y | Y | UC | UC | Y | Y | Y | Y | Y | Y | 81.8 |
| **12.** | Devall 2025 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **13.** | Drayton 2016 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **14.** | Eckerdal 2016 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **15.** | Endres 2023 | N | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 81.8 |
| **16.** | Fein 2021 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **17.** | Flood 2023 | UC | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 81.8 |
| **18.** | Girma 2024 | Y | Y | Y | N | N | Y | Y | Y | Y | N | Y | 72.7 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **19.** | Glenzer 2023 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **20.** | Jung 2024 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **21.** | Kountanis 2020 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **22.** | Latt 2024 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **23.** | Liu 2021 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **24.** | Mehrabadi 2012 | Y | Y | Y | N | N | Y | Y | Y | Y | N | Y | 72.7 |
| **25.** | Meltzer-Brody 2017 | Y | Y | Y | N | N | Y | Y | Y | Y | N | Y | 72.7 |
| **26.** | Michelet 2015 | Y | Y | Y | UC | UC | Y | Y | Y | Y | Y | Y | 81.8 |
| **27.** | Parry-Smith 2021 | Y | Y | Y | Y | Y | Y | Y | Y | N | N | Y | 81.8 |
| **28.** | Parry-Smith 2021a | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **29.** | Reale 2020 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **30.** | Schmitz 2011 | Y | Y | Y | UC | UC | Y | Y | Y | N | N | Y | 63.6 |
| **31.** | Sentilhes 2011 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **32.** | Simsek 2012 | Y | Y | Y | N | N | Y | Y | Y | Y | N | Y | 72.7 |
| **33.** | Tebeka 2019 | UC | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 81.8 |
| **34.** | Thompson 2011 | Y | Y | Y | UC | UC | Y | Y | Y | Y | N | Y | 72.7 |
| **35.** | Tiruneh 2022 | Y | Y | Y | UC | UC | Y | Y | Y | Y | Y | Y | 81.8 |
| **36.** | Tsiga-Ahmed 2024 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **37.** | Ukah 2020 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **38.** | Umashankar 2013 | Y | Y | Y | UC | UC | Y | Y | Y | Y | N | Y | 72.7 |
| **39.** | van Steijn 2020 | Y | Y | Y | UC | UC | Y | Y | Y | Y | N | Y | 72.7 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **40.** | Wang 2022 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **41.** | Wattar 2017 | Y | Y | Y | N | N | Y | Y | Y | Y | N | Y | 72.7 |
| **42.** | Wiley 2024 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |
| **43.** | Yee 2019 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **44.** | Yi 2024 | Y | Y | Y | Y | Y | Y | Y | Y | Y | N | Y | 90.9 |

1. Were the two groups similar and recruited from the same population? 2. Were the exposures measured similarly to assign people to both exposed and unexposed groups? 3. Was the exposure measured in a valid and reliable way? 4. Were confounding factors identified? 5. Were strategies to deal with confounding factors stated? 6. Were the groups/participants free of the outcome at the start of the study (or at the moment of exposure)? 7. Were the outcomes measured in a valid and reliable way? 8. Was the follow up time reported and sufficient to be long enough for outcomes to occur? 9. Was follow up complete, and not, were the reasons to loss to follow up described and explored? 10. Were strategies to address incomplete follow up utilized? 11. Was appropriate statistical analysis used?

Y: Yes, N: No, U: Unclear; NA: Not applicable

| Table S12. Quality assessment of the case-control studies | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Study ID** | **JBI Critical Appraisal Checklist for case-control studies** | | | | | | | | | | |
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **Total (%)** |
| 1. | Bernasconi 2021 | Y | Y | Y | Y | Y | Y | Y | Y | UC | Y | 90.0 |
| 2. | Biele 2022 | Y | Y | Y | Y | Y | Y | Y | Y | UC | Y | 90.0 |
| 3. | Elmas 2022 | Y | Y | Y | Y | Y | Y | UC | UC | UC | Y | 70.0 |
| **4.** | Mitta 2023 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| 5. | Ricbourg 2015 | Y | Y | Y | Y | Y | Y | UC | UC | UC | Y | 70.0 |

1. Were the groups comparable other than the presence of disease in cases or the absence of disease in controls? 2. Were cases and controls matched appropriately? 3. Were the same criteria used for identification of cases and controls? 4. Was exposure measured in a standard, valid and reliable way? 5. Was exposure measured in the same way for cases and controls? 6. Were confounding factors identified? 7. Were strategies to deal with confounding factors stated? 8. Were outcomes assessed in a standard, valid and reliable way for cases and controls? 9. Was the exposure period of interest long enough to be meaningful? 10. Was appropriate statistical analysis used?

Y: Yes, N: No, U: Unclear; NA: Not applicable

| Table S13. Quality assessment of cross-sectional studies | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Study ID** | **JBI Critical Appraisal Checklist for cross-sectional studies** | | | | | | | |
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **Total (%)** |
| **1.** | Adebayo 2024 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **2.** | Anjum 2019 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **3.** | Duhan 2016 | Y | Y | Y | UC | UC | UC | Y | Y | 62.5 |
| **4.** | Elmir 2012 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **5.** | Escobar 2019 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **6.** | Essiben 2025 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **7.** | Fenn 2024 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **8.** | Ketevi 2025 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **9.** | Owolabi 2020 | Y | Y | Y | Y | N | N | Y | Y | 75.0 |
| **10** | Shahbazi Sighaldeh 2020 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **11** | Sotunsa 2019 | Y | Y | Y | Y | UC | UC | Y | Y | 75.0 |
| **12** | Tort 2015 | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |

1. Were the criteria for inclusion in the sample clearly defined? 2. Were the study subjects and the setting described in detail? 3. Was the exposure measured in a valid and reliable way? 4. Were objective, standard criteria used for measurement of the condition? 5. Were confounding factors identified? 6. Were strategies to deal with confounding factors stated? 7. Were the outcomes measured in a valid and reliable way? 8. Was appropriate statistical analysis used?

Y: Yes, N: No, U: Unclear; NA: Not applicable

| Table S14. Quality assessment of the controlled trials | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Study ID** | **JBI Critical Appraisal Checklist for controlled trials** | | | | | | | | | | | | |
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **Total (%)** |
| 1. | Blum 2010 | Y | Y | Y | Y | Y | Y | U | Y | Y | Y | Y | Y | Y | 92.3 |
| **2.** | Cornelissen 2019 | Y | Y | Y | Y | Y | Y | U | Y | Y | Y | Y | Y | Y | 92.3 |
| **3.** | Gallos 2023 | NA | NA | Y | NA | NA | Y | NA | Y | Y | Y | Y | Y | Y | 100.0 |
| **4.** | Hofmeyr 2004 | Y | Y | Y | Y | Y | Y | UC | Y | Y | Y | Y | Y | Y | 92.3 |
| **5.** | Hough 2020 | Y | Y | Y | Y | Y | Y | U | Y | Y | Y | Y | Y | Y | 92.3 |
| **6.** | Lokugamage 2001 | Y | Y | Y | N | Y | Y | U | Y | Y | Y | Y | Y | Y | 84.6 |
| **7.** | Rozenberg 2023 | Y | NA | Y | NA | NA | Y | U | Y | Y | Y | Y | Y | Y | 90.0 |
| **8.** | Walraven 2004 | Y | Y | Y | N | N | Y | U | Y | Y | Y | Y | Y | Y | 76.9 |
| **9.** | Widmer 2010 | Y | Y | Y | Y | Y | Y | U | Y | Y | Y | Y | Y | Y | 92.3 |
| **10.** | Zuberi 2008 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |
| **11.** | WOMAN 2017 | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | 100.0 |

Bias related to selection and allocation:

1. Was true randomization used for assignment of participants to treatment groups?
2. Was allocation to treatment groups concealed?
3. Were treatment groups similar at the baseline?

Bias related to administration of intervention/exposure:

4. Were participants blind to treatment assignment?
5. Were those delivering the treatment blind to treatment assignment?
6. Were treatment groups treated identically other than the intervention of interest?

Bias related to assessment, detection and measurement of the outcome:

7. Were outcome assessors blind to treatment assignment?
8. Were outcomes measured in the same way for treatment groups?
9. Were outcomes measured in a reliable way

Bias related to participant retention:

10. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analysed?

Statistical Conclusion Validity:

11. Were participants analysed in the groups to which they were randomized?
12. Was appropriate statistical analysis used?
13. Was the trial design appropriate and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial?

Y: Yes, N: No, U: Unclear; NA: Not applicable

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