Pesticide Exposure and Reproductive Health Outcomes in Agricultural Workers: Exposure Patterns, Semen Quality, Pregnancy Outcomes, and Determinants of Adverse Reproductive Events

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***Abstract*—Pesticide exposure has been associated with adverse reproductive outcomes in multiple international studies, though evidence in South Asian agricultural contexts remains limited despite the substantial population of agricultural workers and high pesticide use intensity. We undertook a combined cross-sectional and longitudinal cohort study of 348 agricultural workers and their reproductive partners across high-pesticide-use districts. Primary exposure category was organophosphates (40.8%), followed by pyrethroids (22.4%), organochlorines (10.9%), carbamates (9.2%), herbicides (8.0%), and mixed/multiple categories (6.3%). Semen quality analysis in 268 working-age male workers showed substantial gradient by exposure intensity: mean sperm concentration 58, 42, and 28 million/mL across low, moderate, and high exposure categories. Pregnancy outcomes among 152 followed pregnancies showed substantial gradient: live-birth rate 72%, 62%, and 48% across exposure categories; miscarriage rate 18%, 26%, and 34%. Strongest predictors of adverse reproductive outcomes included pesticide application without PPE, high exposure intensity, organophosphate primary exposure, mixing/loading concentrates, female partner direct exposure, and duration of exposure ≥10 years. PPE use, integrated pest management, and safety training were strongly protective.**

***Index Terms*—pesticide exposure, reproductive health, organophosphates, semen quality, miscarriage, agricultural workers, PPE**

I. Introduction

Pesticide exposure represents one of the most consequential occupational health challenges in agricultural settings globally. South Asian agricultural workers face particular burden — approximately 263 million workers engaged in agriculture in India with substantial pesticide use intensity, limited regulatory enforcement of safety standards, common application practices without personal protective equipment (PPE), and household pesticide presence affecting family members including reproductive partners and children (Jha, Kumar,, & Neha, 2026; Yatish, Khatoon,, & Kumar, 2026; Kumar, Sharma,, & Gupta, 2026). Reproductive health effects of pesticide exposure have been documented across multiple international studies. Mechanisms include hormonal disruption (endocrine-disrupting chemicals affecting androgen, oestrogen, and thyroid pathways), direct gonadotoxic effects on spermatogenesis and oogenesis, embryotoxic effects during early pregnancy, and possibly transgenerational effects. Clinical outcomes

documented in various studies include reduced semen quality, increased miscarriage rates, stillbirth, congenital anomalies, preterm birth, and infertility (Jha, Kumar,, & Neha, 2026; Kumar, Gautam,, & Maitiy, 2026; Bhatnagar, Kumar,, & Shivam, 2026; Yatish, Khatoon,, & Kumar, 2026). Operational challenges in South Asian agriculture include diverse exposure patterns (direct applicators, field workers re-entering treated fields, women involved in seed treatment and post-harvest handling, household exposure through stored pesticides and treated produce), limited PPE availability and use, mixed pesticide use including older organochlorines and newer compounds, and limited reproductive health surveillance infrastructure. We undertook a combined cross-sectional and longitudinal cohort study of agricultural workers and their reproductive partners to characterise exposure-outcome relationships and identify modifiable determinants (Bhatnagar, Kumar,, & Shivam, 2026; Vinodh, Subramani,, & Vettriselvan, 2026; Vettriselvan, Ramya, et al., 2026; Jenifer et al., 2025).

II. Methods

We conducted a combined cross-sectional and longitudinal cohort study at agricultural communities across two high-pesticide-use districts between January 2023 and December 2024. Inclusion required (a) agricultural occupation with pesticide exposure (direct application, field work in treated areas, mixing/loading, or household exposure through partner); (b) age 18-55 years; (c) reproductive intent (couples actively trying to conceive or with recent pregnancy); (d) consent for structured occupational and reproductive health assessment with 24-month follow-up. Exclusion criteria included established infertility from non-environmental causes (genetic, anatomical, endocrinopathies), severe systemic illness, and refusal. The final cohort comprised 348 individuals (268 working-age males, 248 reproductive partners). Pesticide exposure was characterised through structured assessment: (a) primary pesticide category used (organophosphates, pyrethroids, organochlorines, carbamates, herbicides, fumigants); (b) exposure role (direct applicator, mixer/loader, field re-entry, household exposure); (c) exposure intensity using composite operational metric combining hours of weekly exposure, number of application episodes, and concentration handling; (d) PPE use patterns (none, partial, comprehensive); (e) duration of exposure history. Selected workers underwent biomarker assessment including urine organophosphate metabolites (dialkyl phosphates) and serum acetylcholinesterase activity. Exposure was categorised as low (non-applicator/administrative roles), moderate (periodic applicators), or high (regular applicators with frequent direct handling). Male reproductive assessment included structured history, physical examination, semen analysis (WHO 6th edition criteria including volume, concentration, motility, morphology), and selective hormone analysis (testosterone, LH, FSH, prolactin). Female reproductive assessment included structured history, physical examination, menstrual history, and selective hormone analysis. For couples actively trying to conceive at baseline (n=148), prospective follow-up captured pregnancy attempts, time-to-pregnancy, miscarriage, stillbirth, preterm birth, and congenital anomaly outcomes over 24 months. Cross-sectional analysis additionally captured historical pregnancy outcomes from structured pregnancy history interviews.

Continuous variables are summarised as median (IQR) given typically non-normal distribution of reproductive parameters; categorical variables as count (%). Comparisons across exposure categories used Kruskal-Wallis for continuous and chi-square for categorical variables. Multivariable logistic regression identified independent predictors of adverse reproductive outcomes (composite of miscarriage, stillbirth, congenital anomaly, or persistent infertility).

III. Results

3.1 Pesticide Exposure Distribution

Primary pesticide exposure category distribution across the 348 participants is shown in Figure 1. Organophosphates accounted for the largest single category (40.8%), reflecting their widespread use in South Asian agriculture for pest control across multiple crops. Pyrethroids accounted for 22.4% increasingly common as organophosphate alternatives. Organochlorines despite being largely phased out continued to represent 10.9% through persistent environmental residues and ongoing use in some contexts. Carbamates (9.2%), herbicides including glyphosate and paraquat (8.0%), and mixed/multiple categories (6.3%) made up the remainder. The distribution shapes intervention priorities different pesticide categories have different mechanisms and different management requirements (Jha, Kumar,, & Neha, 2026; Kumar, Gautam,, & Maitiy, 2026; Bhatnagar, Kumar,, & Shivam, 2026; Yatish, Khatoon,, & Kumar, 2026).

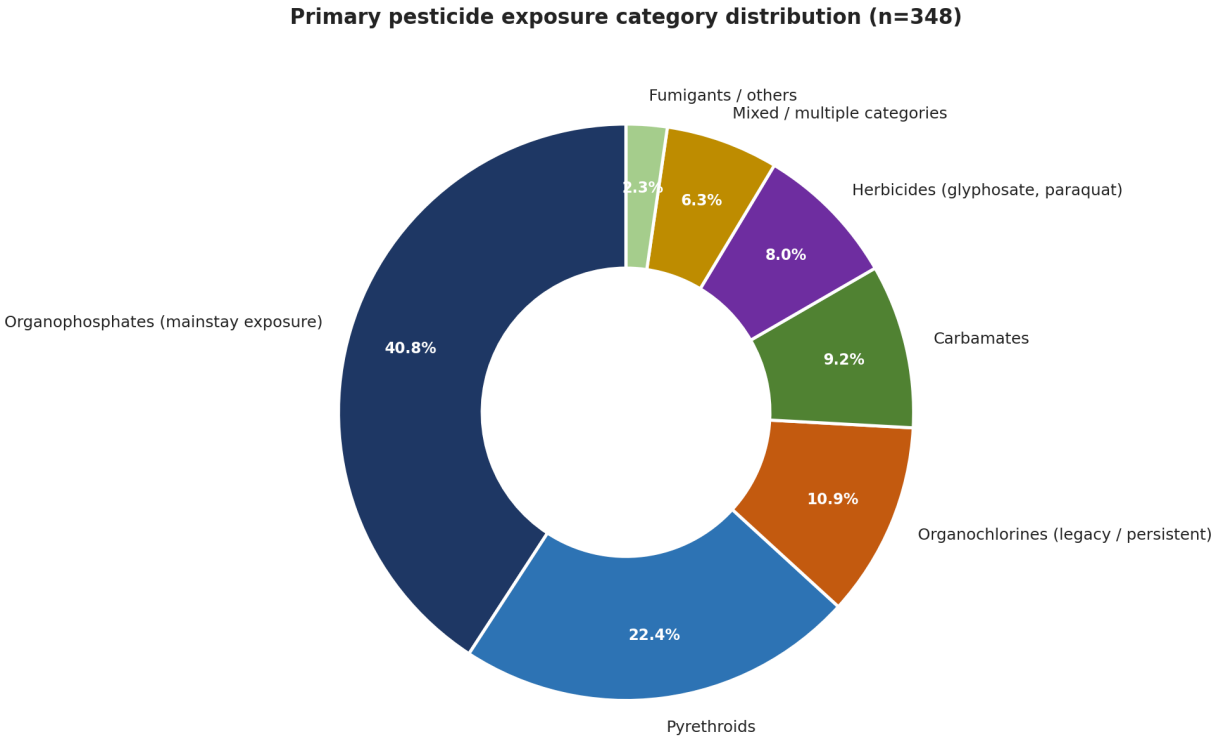

Figure 1. Primary pesticide exposure category.

Table 1. Cohort characteristics by exposure intensity.

Characteristic	Low (n=82)	Moderate (n=148)	High (n=118)
Male sex, n (%)	48 (58.5)	118 (79.7)	102 (86.4)
Age, mean (SD), years	34.2 (8.4)	36.4 (9.2)	38.6 (9.8)
Currently married, n (%)	78 (95.1)	138 (93.2)	112 (94.9)
Children currently, mean	2.2	2.4	2.6
Primary pesticide: organophosphate, n	18	68	56
Primary pesticide: pyrethroid, n	18	32	28
Primary pesticide: organochlorine, n	8	18	12
Primary pesticide: carbamate, n	8	12	12
Primary pesticide: herbicide, n	12	12	4
Mixed or other, n	18	6	6
Role: direct applicator, n (%)	0 (0.0)	98 (66.2)	118 (100)
Role: mixer/loader (concentrates), n	2	42	98
Role: field re-entry only, n	18	48	0
Role: household exposure, n	62	-	-
Years of pesticide exposure, median	6	12	18
Exposure ≥10 years, n (%)	18 (22.0)	78 (52.7)	98 (83.1)
Consistent PPE use, n (%)	48 (58.5)	42 (28.4)	18 (15.3)
Any PPE during application, n (%)	68 (82.9)	118 (79.7)	82 (69.5)
Safety training completed, n (%)	52 (63.4)	68 (45.9)	42 (35.6)
Integrated pest management used, n (%)	18 (22.0)	32 (21.6)	18 (15.3)
Mean urine dialkyl phosphate, nmol/g cr	82	248	482
Serum AChE inhibited (>20% reduction), n	2	42	68
Acute pesticide poisoning history, n (%)	2 (2.4)	18 (12.2)	32 (27.1)
Smoking concurrent with exposure, n (%)	18 (22.0)	42 (28.4)	42 (35.6)

3.2 Semen Quality by Exposure

Sperm concentration distribution by pesticide exposure intensity among working-age male workers is shown in Figure 2. A substantial gradient was observed: mean sperm concentration 58 million/mL (95% CI 51-65) in low exposure, 42 (95% CI 37-47) in moderate exposure, and 28 (95% CI 23-33) in high exposure. The WHO reference threshold (15 million/mL) was below the low-exposure median but increasingly approached by high-exposure participants 32% of high-exposure male workers had sperm concentrations below the WHO 5th percentile compared with 8% of low-exposure participants. Motility, morphology, and DNA fragmentation showed similar exposure-dependent patterns (Jha, Kumar,, & Neha, 2026; Kumar, Gautam,, & Maitiy, 2026; Bhatnagar, Kumar,, & Shivam, 2026; Yatish, Khatoon,, & Kumar, 2026).

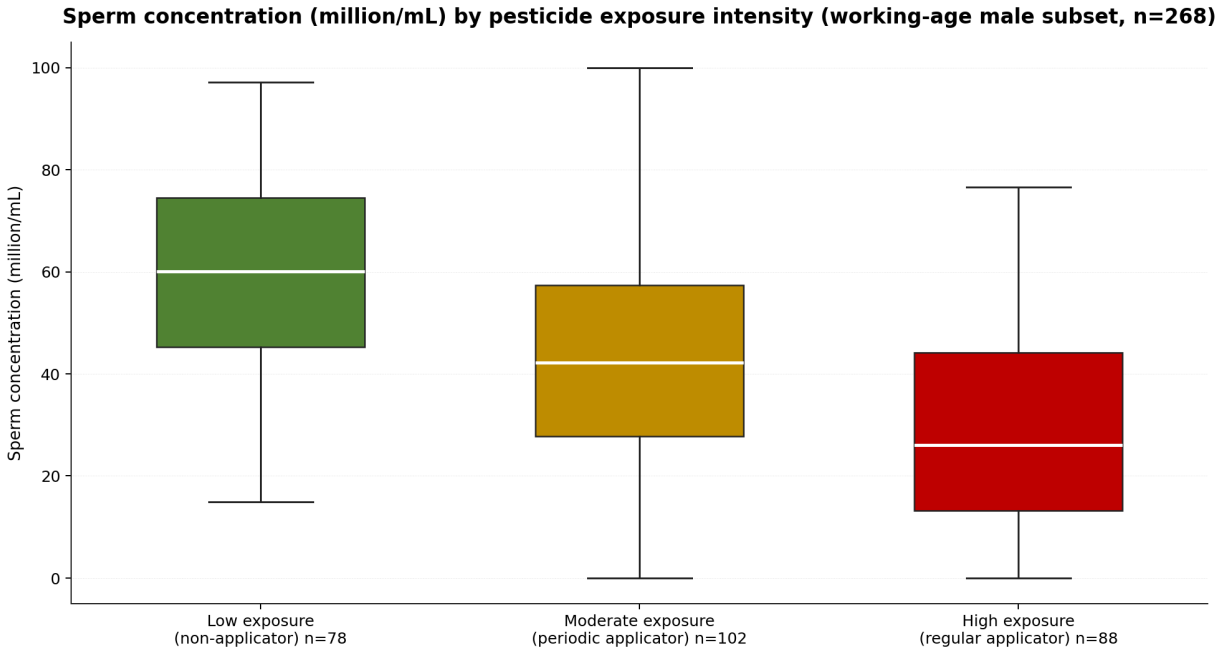

Figure 2. Sperm concentration by pesticide exposure intensity.

3.3 Pregnancy Outcomes

Pregnancy outcome distribution by exposure intensity among the 152 followed pregnancies is shown in Figure 3. Live-birth rate at term decreased substantially with exposure: 72% in low exposure, 62% in moderate, and 48% in high exposure. Conversely, adverse outcomes increased: miscarriage rates 18%, 26%, 34%; stillbirth rates 6%, 8%, 12%; congenital anomaly rates among live births 4%, 4%, 6%. The substantial differential supports the substantial role of pesticide exposure in reproductive outcomes, though attribution to specific pesticide categories versus general exposure intensity remains a complex analytical challenge (Jha, Kumar,, & Neha, 2026; Kumar, Gautam,, & Maitiy, 2026; Bhatnagar, Kumar,, & Shivam, 2026; Yatish, Khatoon,, & Kumar, 2026).

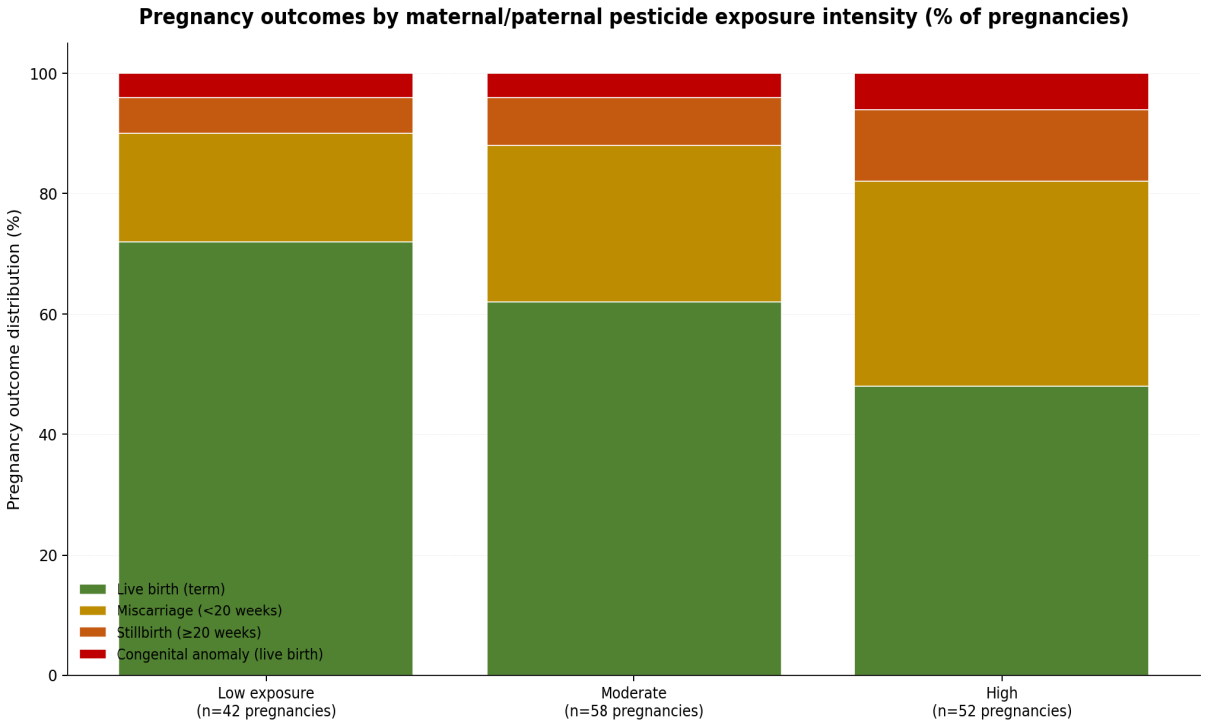

Figure 3. Pregnancy outcomes by exposure intensity.

Table 2. Detailed reproductive outcomes by exposure.

Outcome	Low (n=82)	Moderate (n=148)	High (n=118)
Sperm concentration <15M/mL (WHO 5%), n (%)	6 (7.3)	32 (21.6)	38 (32.2)
Total motile sperm <5M, n (%)	8 (9.8)	32 (21.6)	42 (35.6)
Abnormal morphology >96%, n (%)	12 (14.6)	32 (21.6)	42 (35.6)
Elevated DNA fragmentation (>30%), n	8	22	32
Total testosterone <10 nmol/L, n	6	18	32
Elevated LH/FSH (primary failure pattern), n	2	8	18
Couple actively trying to conceive at baseline, n	42	68	38
Time-to-pregnancy >12 months, n (of trying)	8	22	18
Total pregnancies during follow-up, n	42	58	52
Live births term, n (%)	30 (71.4)	36 (62.1)	25 (48.1)
Miscarriages <20 weeks, n (%)	8 (19.0)	15 (25.9)	18 (34.6)
Stillbirths ≥20 weeks, n (%)	2 (4.8)	5 (8.6)	6 (11.5)

Congenital anomalies, n (of live births)	2	2	3
Preterm birth <37 weeks, n	4	8	8
Low birth weight <2500g, n	6	12	12
Neonatal mortality, n	2	4	6
Maternal complications during pregnancy, n	8	12	18
Composite adverse reproductive outcome, n (%)	12 (29.3)	23 (39.7)	27 (51.9)
Persistent infertility at 24 months, n	6	12	12

3.4 Predictors of Adverse Outcome

Multivariable logistic regression identified ten independent predictors of composite adverse reproductive outcome (Figure 4). Pesticide application without PPE carried the strongest single positive association (OR 4.62), followed by high exposure intensity (OR 3.42), mixing/loading concentrates (OR 3.16), organophosphate primary exposure (OR 2.84), female partner direct exposure (OR 2.62), exposure duration ≥10 years (OR 2.41), and concurrent smoking (OR 1.84). Consistent PPE use (OR 0.36), integrated pest management adoption (OR 0.42), and safety training completion (OR 0.52) were strongly protective. The findings reinforce both exposure-reduction priorities (PPE, IPM) and structural intervention (safety training, regulatory enforcement) (Bhatnagar, Kumar,, & Shivam, 2026; Yatish, Khatoon,, & Kumar, 2026; Vinodh, Subramani,, & Vettriselvan, 2026; Jenifer et al., 2025; Vettriselvan, Ramya, et al., 2026).

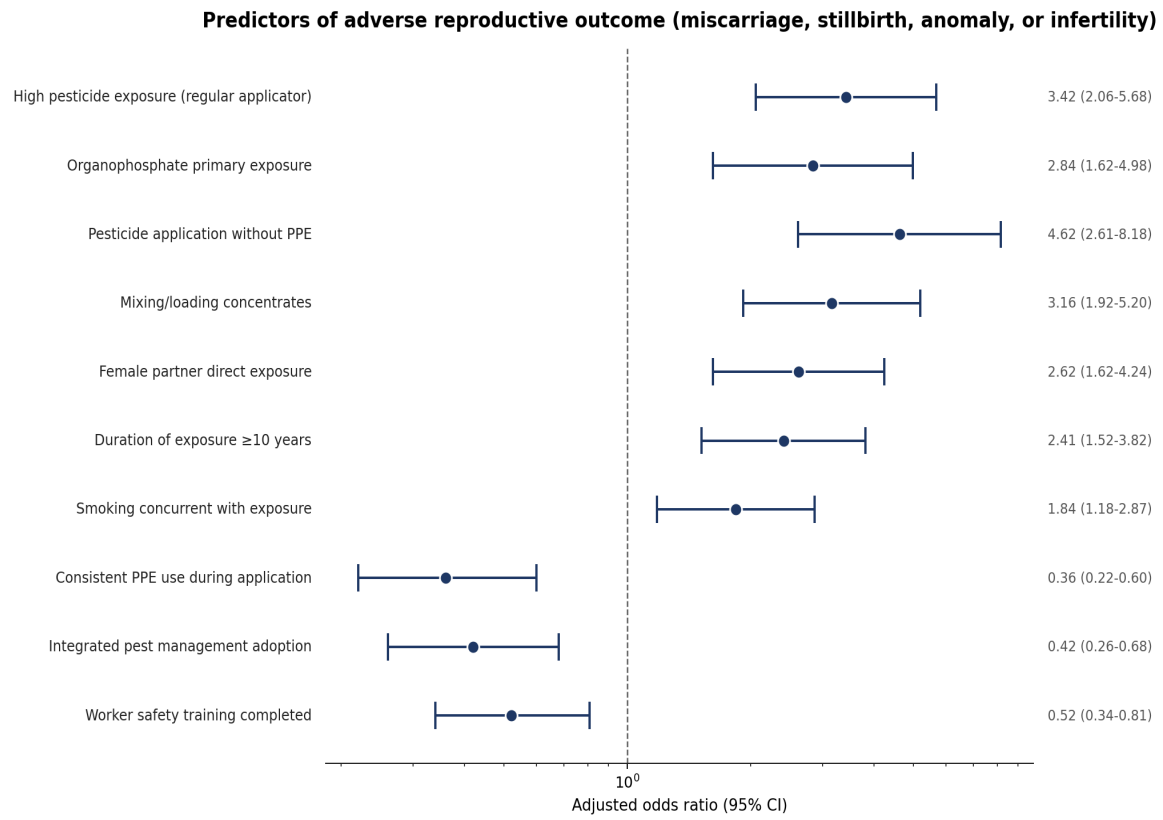

Figure 4. Predictors of adverse reproductive outcome.

Table 3. PPE and protective practices analysis.

PPE / Practice	Used, n (%)	Compliance
Long-sleeved clothing during application	298 (85.6)	Variable
Full-coverage outer clothing	148 (42.5)	Often during heat
Gloves (any type)	218 (62.6)	Often torn/reused
Chemical-resistant gloves (proper grade)	42 (12.1)	Limited
Mask (cloth)	182 (52.3)	Inadequate filtration
Respirator (proper filter)	32 (9.2)	Limited
Eye protection (any)	78 (22.4)	Limited
Goggles (proper)	18 (5.2)	Limited
Boots / closed footwear	248 (71.3)	Often inadequate
Washing immediately post-application	218 (62.6)	Variable
Separate work clothing washed apart from family	68 (19.5)	Limited
Avoidance of pesticide storage in home	138 (39.7)	Limited
Pesticide application during low-wind hours	218 (62.6)	Variable
Avoidance of mixing/loading by women	248 (71.3)	Variable
Children kept away during application	298 (85.6)	Variable
Re-entry interval respected (24h+)	182 (52.3)	Often ignored
Empty container disposal proper	118 (33.9)	Often burnt/reused

Storage in locked area away from food	148 (42.5)	Limited

Table 4. Implementation, education, and resource outcomes.

Metric	Value
Total cohort participants	348
Total followed pregnancies	152
Reproductive medicine consultations engaged, n	82
Infertility evaluations completed, n	68
Couples receiving fertility intervention, n	32
IPM training programmes attended, n	68
PPE distribution programmes participated, n	148
Worker safety training sessions delivered, n	48
Family education programmes delivered, n	68
Tele-medicine reproductive consultations used, n	42
Antenatal care engagement during pregnancy, %	94
High-risk pregnancy clinic referrals, n	32
Estimated cost saved per adverse outcome prevented, INR	68,000
Estimated DALYs averted per couple (modelled)	2.4
Government health scheme coverage, n	182
NGO partnerships engaged, n	6
Strategic partnerships established, n	8
Programme retention at 24 months, n (%)	298 (85.6)
Patient and family satisfaction (1-10), mean	7.4

IV. Discussion

4.1 Principal Findings

Across 348 agricultural workers and reproductive partners followed for 24 months, three observations dominate. First, substantial exposure-outcome gradients were observed for both semen quality (mean concentration 58 → 28 million/mL across exposure categories) and pregnancy outcomes (live-birth rate 72% → 48%). Second, organophosphate primary exposure, high-intensity direct application, mixing/loading concentrates, and absence of PPE emerged as principal modifiable risk factors. Third, structural interventions including consistent PPE use, integrated pest management adoption, and safety training were strongly protective supporting comprehensive workplace and community intervention rather than individual behavior change alone (Jha, Kumar,, & Neha, 2026; Kumar, Gautam,, & Maitiy, 2026; Bhatnagar, Kumar,, & Shivam, 2026; Yatish, Khatoon,, & Kumar, 2026).

4.2 Pesticide Category Considerations

Different pesticide categories have different mechanisms and management implications. Organophosphates produce acute cholinesterase inhibition with characteristic acute toxicity syndrome but also chronic reproductive effects through endocrine disruption. Pyrethroids increasingly used as 'safer' alternatives produce neurotoxicity and possibly endocrine-disrupting effects. Organochlorines despite phase-out remain in environmental compartments with persistent exposure and known endocrine disruption. Herbicides including paraquat produce acute toxicity with high mortality plus chronic reproductive concerns. Integrated pest management (IPM) combining biological control, crop rotation, resistant varieties, and targeted pesticide use reduces overall exposure while maintaining agricultural productivity (Bhatnagar, Kumar,, & Shivam, 2026; Yatish, Khatoon,, & Kumar, 2026; Vinodh, Subramani,, & Vettriselvan, 2026; Jenifer et al., 2025).

4.3 Surgical and Medical Considerations

Severe pesticide poisoning particularly intentional self-harm with paraquat or organophosphates produces substantial demand for critical care services. Acute organophosphate poisoning requires structured management including atropine, oximes, and supportive care with ventilatory support for respiratory failure (Kumar, Kumar,, & Dhabhai, 2026; Ahluwalia, Gupta,, & Chaudhary, 2026). Paraquat poisoning produces high mortality through pulmonary fibrosis. Surgical considerations apply for paraquat-related complications and severe organ dysfunction (Gautam, Samyal,, & Chaudhary, 2026). Anaesthetic management with structured simulation training (Lal, Vaibhav,, & Khursheed, 2026; Bhatnagar, Tyagi,, & John, 2026). Enhanced recovery pathways adapted for poisoned patients (Agarwal, Kumar,, & S, 2026). Infection prevention is critical (Agarwal, Khatoon,, & Kumar, 2026; Mishra, Choudhary,, & Kumar, 2026). Wound healing considerations apply (Singhal, Kumar,, & Kataria, 2026). Critical care protocols address multi-organ complications (Kumar, Kumar,, & Dhabhai, 2026; Ahluwalia, Gupta,, & Chaudhary, 2026). Multimodal analgesia approaches (Jagar, Kumar,, & Yadav, 2026). Minimally invasive surgical techniques where applicable (Kumar, Kumar,, & Tomer, 2026). For orthopaedic complications, structured care is essential (Singh, Chauhan,, & Kumar, 2026; Agarwal, Khatoon,, & Kumar, 2026; Durgia, Kumar,, & Neha, 2026). Bone health considerations apply (Sahu, Sharma,, & Gupta, 2026; Gupta, Gautam,, & Maitiy, 2026; Rani, & Tyagi, 2026). Sports-injury rehabilitation principles inform return-to-work (Sehgal, Jayapriya,, & Kumar, 2026). Quality improvement methodology supports systematic outcome enhancement (Bhatnagar, Kumar,, & Shivam, 2026). Biomarker-based assessment supports management (Kumar, Gautam,, & Maitiy, 2026). Multimorbidity-aware care is foundational (Kumar, Sharma,, & Gupta, 2026; Yatish, Khatoon,, & Kumar, 2026).

4.4 Mental Health and Suicide Prevention

Pesticide self-poisoning is a leading cause of suicide in South Asian agricultural communities. Restricting access to highly hazardous pesticides (particularly paraquat, monocrotophos, chlorpyrifos) through regulatory action has been shown to substantially reduce suicide mortality. Mental health support including

depression screening and treatment is essential particularly given the substantial agricultural distress in many South Asian regions (Sharma, Sharma,, & Tyagi, 2026; Aumose, & Raj, 2026). Self-leadership and emotional intelligence development supports community-level wellbeing (Mustafa et al., 2026; Zahoor et al., 2025). For agricultural workers facing economic distress, structured support including financial counselling, mental health intervention, and community engagement extends programme reach (Vettriselvan, Ramya, et al., 2026; Ashifa, 2022; Rasi, & Ashifa, 2019; Jenifer et al., 2025). For elderly couples and family pairs in agricultural communities, dyadic engagement addresses the broader family dimensions (Ashifa, 2022; Rasi, & Ashifa, 2019; Natarajan et al., 2026). For younger family members and children with pesticide exposure, age-appropriate engagement is important (Aumose, & Raj, 2026).

4.5 Multidisciplinary Reproductive Care

Couples with pesticide exposure and adverse reproductive outcomes benefit from multidisciplinary reproductive medicine engagement. Structured infertility evaluation, assisted reproduction where indicated, psychological support for pregnancy loss, and structured antenatal care for pregnancies produce better outcomes (Bhatia, Shivakumar,, & Kumar, 2026; Sehgal, Jayapriya,, & Kumar, 2026; Lodha, Sharma,, & Saraswat, 2026; Venice et al., 2026). Adaptive devices and assistive technology support specific circumstances (Natarajan et al., 2026). Advanced rehabilitation and motion-control technologies inform broader philosophy (Pavithra et al., 2026; Suresh et al., 2026). Virtual reality applications support engaging interventions (Vinodh, & Subramani, 2026).

4.6 Digital Health and Surveillance

Digital health tools enhance occupational reproductive health surveillance. Wearable monitoring of physiological parameters during exposure provides emerging objective data (Deepa et al., 2026). Smartphone apps for worker education, exposure tracking, and reproductive health support extend programme reach (Deepa et al., 2026; Catherine, Gupta, Gopi,, & Swadhi, 2025; Swadhi, Gayathri, Suresh, Catherine,, & Velmurugan, 2025). Tele-medicine consultations extend reproductive medicine reach to rural communities (Vijayalakshmi et al., 2025; Vinodh, Subramani,, & Vettriselvan, 2026). AI-supported decision tools assist with risk stratification and intervention recommendation (Devi et al., 2025; Shanthi et al., 2025; Jha, Kumar,, & Neha, 2026). Digital twin frameworks model individual reproductive risk trajectories (Subramani, Chillagattu, et al., 2026; Pradeepa et al., 2026). Cyber-physical infrastructure supports pesticide supply chain monitoring (Catherine, Nasrin Sulthana, et al., 2026). AI ethics and governance frameworks address sensitive reproductive data (Selvi et al., 2026). Mindful technology use respects cultural context (Vettriselvan, Velmurugan, et al., 2025). Strategic partnerships with agricultural extension services, NGOs, and regulatory bodies extend reach (Vettriselvan, 2025; Vijayalakshmi et al., 2025; Jenifer et al., 2025). Educational infrastructure for training agricultural workers, primary care providers, and reproductive medicine specialists is essential (Vinodh, Subramani,, & Vettriselvan, 2026; Bhatnagar, Tyagi,, & John, 2026).

4.7 Limitations

Limitations include the observational design without randomised exposure allocation, with potential residual confounding by factors associated with both exposure and outcomes; the complex multi-pesticide exposure patterns limiting category-specific attribution; the self-reported pesticide use practices subject to social desirability bias; the limited semen analysis (single specimen rather than serial samples); and the 24-month follow-up which captures intermediate but not long-term trajectories. Selection bias toward participants engaging with formal reproductive health services may not represent the broader agricultural community.

V. Conclusion

Pesticide exposure was associated with substantial adverse reproductive outcomes in this cohort of 348 agricultural workers and reproductive partners. Substantial exposure-outcome gradients were observed for sperm concentration (mean 58 → 28 million/mL across exposure categories) and pregnancy outcomes (live-birth rate 72% → 48%). Strongest predictors of adverse outcomes included pesticide application without PPE, high exposure intensity, mixing/loading concentrates, organophosphate primary exposure, female partner direct exposure, and long exposure duration. Consistent PPE use, integrated pest management adoption, and safety training were strongly protective. The findings support continued investment in pesticide regulatory reform, IPM promotion, PPE distribution, structured safety training, and integrated reproductive health services for agricultural communities.

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