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Research Article

Keywords: Pesticide neurotoxicity, Economic burden, Intellectual disability, Parkinson's disease, Middle East and North Africa, Policy intervention

Posted Date: June 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9670402/v1

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Additional Declarations: No competing interests reported.

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Abstract

Background and Objectives: Pesticide-attributable neurological disease — intellectual disability (ID) from gestational organophosphate exposure and Parkinson's disease (PD) from occupational exposure — imposes a substantial but unquantified economic burden across the Middle East and North Africa (MENA). We estimated the total economic cost across 18 MENA countries (2010–2023) and evaluated the return on investment of four pesticide-reduction interventions.
Methods: A societal costing framework was applied across 252 country-year observations, integrating GBD-consistent epidemiological estimates with World Bank, ILOStat, and cost-of-illness data. Direct healthcare costs, indirect productivity losses, and intangible quality-of-life costs were quantified. Four interventions were evaluated using benefit-cost ratios, cost-effectiveness ratios, and net present value.
Results: Total regional burden reached USD 83.4 billion (mean USD 5.96 billion annually): direct costs 52.9%, indirect 26.5%, intangible 20.6%. ID drove 87.6% of direct expenditures. Three interventions were cost-beneficial: Surveillance System (BCR 11.0; USD 651/DALY), PPE Programme (BCR 3.25; USD 2,796/DALY), and Buffer Zones (BCR 2.23; USD 3,138/DALY).
Conclusions: Pesticide-attributable neurological disease represents a major preventable burden across MENA. The surveillance system offers exceptional return on investment as a first-line policy action.

Keywords

Pesticide neurotoxicity; Economic burden; Intellectual disability; Parkinson's disease; Middle East and North Africa; Policy intervention

Highlights

- Pesticide-attributable neurological disease cost MENA USD 83.4B over 2010–2023
- Intellectual disability drove 87.6% of direct costs across all 18 countries
- Yemen's burden consumed a mean 18.7% of its national health budget annually
- Surveillance system offered best return: BCR 11.0, USD 651 per DALY averted

- Egypt, Yemen, and Morocco identified as highest-priority investment targets

Introduction

Pesticides are a key agricultural input used to protect seeds and safeguard crops, and FAO reports that global pesticide use in agriculture reached 3.73 million tonnes in 2023, a 14% increase in a decade and a doubling since 1990 (FAO 2024). Certain pesticides are linked to PD; epidemiological and animal studies argue for a causal relationship, and occupational inhalation/skin exposure is a recognized risk (Atterling Brolin, Schaeffer et al. 2025) through oxidative stress and dopaminergic neurodegeneration in occupationally exposed adults. Additionally, Prenatal and early-childhood pesticide exposure, including carbamates and chlorpyrifos, has been associated with worse neurodevelopmental outcomes, and OP neurotoxicity is plausibly mediated by acetylcholinesterase inhibition (Vidair 2004, Coleman, Asad et al. 2025). Globally, 85% of global IDII DALYs concentrated in low-resource regions including Middle East (Liu, Zhang et al. 2025).

Despite the scale of this burden, its economic dimensions have never been systematically quantified for the MENA region. Existing health economic evidence on pesticide-attributable neurological disease is overwhelmingly derived from high-income settings — primarily Australia, the United States, and Western Europe — where regulatory frameworks, healthcare infrastructure, and cost-of-illness data are mature (Arora, Goodall et al. 2020, Wijers, Ravi et al. 2024). The evidence gap is particularly consequential for MENA, where approximately 30 million agricultural workers apply pesticides under minimal regulatory oversight, where 180 million rural residents face ongoing environmental exposure, and where health systems in several countries are operating at or below minimum functional capacity (Katoue, Cerda et al. 2022, Sherif, Makame et al. 2023, Darwish, Samy et al. 2026). Without economic evidence, pesticide-attributable neurological diseases are less likely to be visible in budget-setting processes that prioritize quantified costs.

High fertility, population ageing, political instability, and weak regulatory enforcement amplify both exposure and vulnerability across MENA, making it simultaneously the world's most important and most understudied region for pesticide-neurological disease economics (Safiri, Noori et al. 2023, Su, Cui et al. 2025, WDI 2026). This study addresses that gap by estimating the total economic burden of pesticide-attributable ID and PD across 18 MENA countries over 14 years (2010–2023), and by conducting a comparative return-on-investment analysis of four pesticide-reduction policy interventions. The primary aim was to quantify annual direct healthcare expenditures, indirect productivity losses, and intangible quality-of-life costs attributable to these conditions, and to identify which policy interventions offer maximum return on investment given MENA-specific disease burden, implementation feasibility, and economic contexts. This analysis is intended to provide the first comprehensive economic evidence base to support regional policy prioritisation, national health budget planning, and international donor investment in pesticide-related neurological disease prevention across MENA.

Methods

Study Design and Setting

This study is a health economic costing analysis estimating the total economic burden of pesticide-attributable neurological disease — specifically intellectual disability (ID) and Parkinson's disease (PD) — across 18 Middle East and North Africa (MENA) countries over 14 years (2010–2023), generating 252 country-year observations. Burden was quantified across three cost dimensions: direct healthcare expenditures, indirect productivity losses, and intangible quality-of-life costs. Return on investment (ROI) was assessed for four pesticide-reduction policy interventions. The analysis adopts a societal costing perspective. All monetary values are expressed in 2020 USD purchasing power parity (PPP) unless stated otherwise.

Epidemiological Foundation

Economic calculations were grounded in companion GBD-consistent epidemiological estimates quantifying pesticide-attributable disease burden for the same 18 countries and study period. These yielded a regional mean of 568,329 disability-adjusted life-years (DALYs) per year (2010–2023 aggregate), comprising 90.3% attributable to

neurodevelopmental ID and 9.7% to PD. Country-year-specific attributable deaths, attributable ID cases, and total DALYs served as denominators for all economic calculations. Full epidemiological methods are reported separately (Darwish, Samy et al. 2026).

Data Sources

Five principal data streams were integrated: epidemiological inputs (Darwish, Samy et al. 2026); World Bank macroeconomic series (GDP per capita, health expenditure, GNI, population, agricultural employment, rural population); ILOStat wage data; FAOSTAT pesticide statistics; and a systematic review of 36 cost-of-illness studies. All costs are expressed in constant 2020 USD PPP. Data gaps for Yemen, Syria, Sudan, Qatar, and Jordan were addressed using World Bank deflator adjustments and linear extrapolation for conflict-affected settings; all imputations are flagged in Supplementary Table S1.

Agricultural wages were extracted from ILOStat for six countries; for the remaining 12, annual wage was estimated as 40% of GDP per capita, consistent with LMIC development economics benchmarks (Cheong, Jansen et al. 2013). These estimates are designated low quality and subjected to sensitivity analyses.

Healthcare cost parameters were identified through a systematic literature search in PubMed (2010–2024) using three query strategies targeting ID costs, PD costs, and MENA neurological expenditure. Thirty-six studies were identified; four originated from MENA countries directly. All non-USD costs were converted to 2020 USD PPP using documented exchange rates and Consumer Price Index inflation multipliers. Data quality assessments, including macroeconomic imputations and conflict-related reliability concerns, are documented in Supplementary Table S1.

Direct Healthcare Cost Parameters: Intellectual Disability

A severity-weighted blended per-case cost of USD 6,471 per child per year was derived from Arora (Arora, Goodall et al. 2020), applying the healthcare cost share reported by Schofield (Schofield, Shrestha et al. 2024) and severity multipliers of 0.5× (mild), 1.0× (moderate), and 2.0× (severe), with a fixed distribution of 20% mild, 50% moderate, and 30% severe. Full derivation is provided in Supplementary Table S1.

Direct Healthcare Cost Parameters: Parkinson's Disease

Per-patient annual direct costs of USD 5,065 were derived from Zhang et al. (Zhang, Zhou et al. 2022), supplemented by estimated medication and rehabilitation costs excluded from insurance claims data in LMIC settings, including dopamine agonists and monoamine oxidase inhibitors typically paid out-of-pocket (Ragothaman, Govindappa et al. 2006). This estimate was applied uniformly across all 18 countries and all 14 study years. Full component breakdown is provided in Supplementary Table S1. A PD severity distribution of 40% mild, 35% moderate, and 25% severe was used in prevalence weighting as a modelling assumption, though severity-specific cost differentials were not applied to PD given the absence of severity-stratified cost data for this population. A community-based Egyptian study reported 57.6% of cases in Hoehn & Yahr stages I–II, 24.2% in stage III, and 18.2% in stages IV–V, which is the closest reliable LMIC/MENA staging distribution found (El-Tallawy, Farghaly et al. 2013, Achbani, Ait Wahmane et al. 2020).

A uniform cost approach was applied across all countries given the absence of defensible country-specific parameters; ±50% uncertainty bounds capture plausible income-spectrum variation. The HIC benchmark from Wijers et al. (Wijers, Ravi et al. 2024) (approximately USD 10,508 per patient per year) was retained as an upper-bound sensitivity reference only.

Indirect Cost Estimation

Indirect costs comprised three components, all discounted at 4.5% annually (sensitivity: 0%, 3%, 6%). Productivity loss from premature PD mortality was calculated using a fixed assumption of mean age at death of 72 years with

three remaining working years — a conservative lower-bound estimate, as occupationally exposed agricultural workers may develop PD at younger ages (Ishihara, Cheesbrough et al. 2007).

Absenteeism losses assumed 30% of ID cases have an economically active caregiver absent 10 days per year, and 60% of employed PD cases are absent 20 days per year. Daily wage was calculated as annual wage divided by 365. Present values were computed over a 20-year horizon using standard annuity formulae. Reduced work capacity losses assumed 20% employment rate and 40% productivity reduction for ID patients aged 18–65 over 30 working years, and 60% employment rate with 30% average productivity reduction for PD patients aged 40–65 over 15 working years, both discounted at 4.5%.

Intangible Cost Estimation

Quality-of-life losses were valued using the Human Capital (HC) approach as the primary method, valuing one DALY at the annual agricultural wage of the exposed population (Jo 2014). Sensitivity analyses applied WHO 1× and 3× GDP per capita thresholds and a VSL approach (USD 200,000–500,000 per premature PD death).

Policy Intervention Analysis

Four pesticide-reduction interventions were modelled: a national regulatory ban on organophosphate and carbamate pesticides (Chemical Ban); mandatory 30–50 metre buffer zones around residential and educational areas (Buffer Zones); a structured PPE provision and occupational safety training programme (PPE Programme); and a national occupational health registry with pesticide biomonitoring and poisoning surveillance (Surveillance System).

Health impact for each intervention was quantified as DALYs averted per year using efficacy estimates derived from peer-reviewed evidence of exposure reduction in comparable settings, translated to disease-risk reductions through documented assumptions about proportionality between exposure and risk, latency periods (15–20 years for PD), and real-world compliance in LMIC contexts. Central efficacy estimates were derived from natural experiments and field studies in comparable settings: chemical ban (20% PD reduction, 6% ID reduction) (Wesseling, McConnell et al. 1997, Gunnell, Eddleston et al. 2007, Knipe, Gunnell et al. 2017), buffer zones (10% PD, 35% ID) (Dereumeaux, Fillol et al. 2020, Moore, Priest et al. 2022), PPE programme (30% PD, 0–5% ID) (Fenske 1988, Levesque, Arif et al. 2012), and surveillance system (10% both) (Keifer 2000, WHO 2015). Full uncertainty ranges are provided in Supplementary Table S2.

Annual implementation costs ranged from USD 4.2 million (Surveillance System) to USD 897.8 million (chemical ban) for a representative MENA country, with ±50% uncertainty ranges. ROI metrics comprised BCR, CER (USD per DALY averted), payback period, and NPV at 5- and 20-year horizons, all discounted at 4.5%. The WHO highly cost-effective threshold was set at USD 31,201 per DALY averted (1× unweighted mean GDP per capita across 18 MENA countries, 2010–2023); sensitivity analyses using the 2020 median (USD 11,904) confirmed that all three viable interventions remained highly cost-effective under this conservative threshold (Fojtíková and Fiala 2026).

Country Prioritisation

Countries were ranked by a composite priority score combining absolute disease burden in DALYs (40%), per capita DALY rate per 100,000 (30%), and implementation feasibility scored 1–5 based on health system capacity, policy readiness, and conflict status (30%). Countries were categorised as Tier 1 Urgent (ranks 1–6), Tier 2 Important (ranks 7–12), or Tier 3 Consider (ranks 13–18).

Data Quality and Sensitivity Analysis

Three countries required explicit data handling. Iraq: pesticide intensity was censored for 8 of 14 years (2013–2020), producing near-zero burden estimates that should not be interpreted as genuinely low disease burden; sensitivity analysis confirmed the headline regional total is robust to Iraq data treatment (Supplementary Table S1). Syria and Yemen carry "High" uncertainty classification for conflict years, with GDP data imputed and flagged in Supplementary Table S1.

Uncertainty ranges of ±50% were applied to all healthcare and intervention cost estimates. Health impact efficacy was varied ±30%. Discount rates ranged 0–6% (base 4.5%). Wage estimates for 12 countries without ILOStat data were designated low quality and subjected to sensitivity sweeps. Tornado diagrams ranked parameters by their influence on BCR and CER. Scenario analyses compared best-case (maximum efficacy, minimum cost, 0% discount), worst-case (minimum efficacy, maximum cost, 6% discount), and base-case results across all four interventions.

Results

Regional Economic Burden

The total economic burden of pesticide-attributable intellectual disability and Parkinson's disease across 18 MENA countries amounted to USD 83.4 billion (USD 83.0 billion excluding Iraq, whose burden estimates for 2013–2020 are censored and carry very high uncertainty; see Methods) over the 14-year study period (2010–2023), equivalent to a regional mean of USD 5.96 billion annually (range USD 4.90 billion in 2010 to USD 6.58 billion in 2014; Table 1).

Table 1. Regional Economic Burden by Component. MENA region (2010-2023).

COMPONENT	14-YR TOTAL (USD BILLION)	ANNUAL MEAN (USD BILLION)	% OF TOTAL
Direct Healthcare	44.2	3.15	52.9
Indirect Productivity	22.1	1.58	26.5
Intangible (Human Capital)	17.2	1.23	20.6
TOTAL	83.4	5.96	100.0

Direct healthcare expenditures were the dominant cost component throughout, comprising 52.9% of total burden (USD 44.2 billion cumulative), followed by indirect productivity losses at 26.5% (USD 22.1 billion) and intangible quality-of-life costs at 20.6% (USD 17.2 billion) under the Human Capital valuation method (Figure 1).

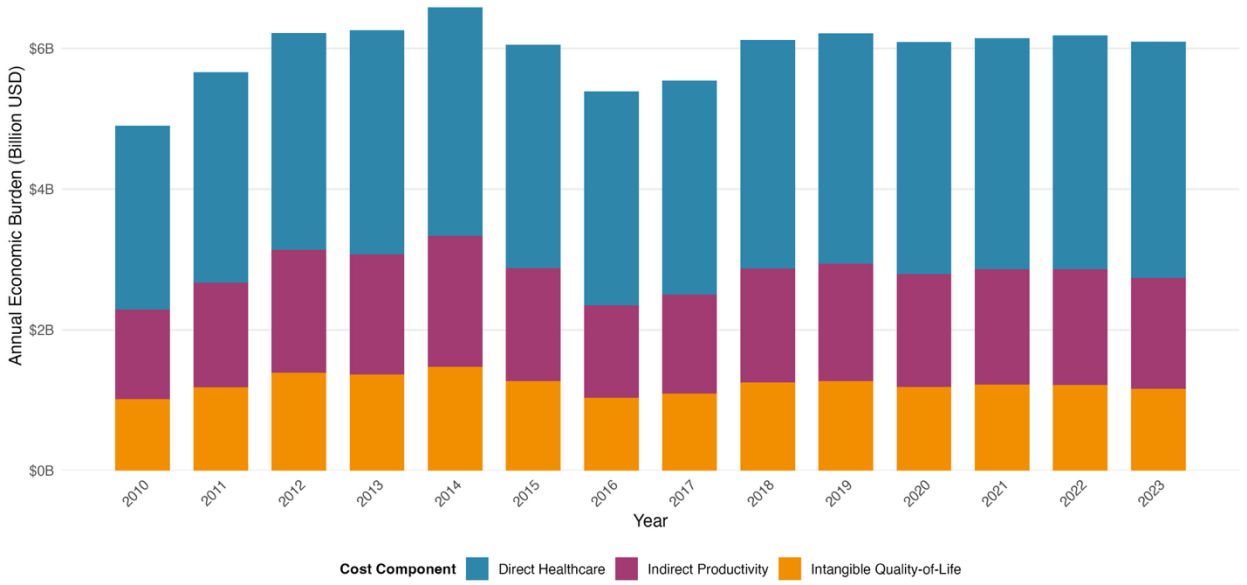


Figure 1. Total Annual Economic Burden of Pesticide-Attributable Neurological Disease in MENA Region by Cost Component (2010-2023). *Stacked bar chart showing direct healthcare costs (blue), indirect productivity losses (purple), and intangible quality-of-life costs (orange) across 18 MENA countries. Intangible costs valued using Human Capital method (1 DALY = annual agricultural wage of the exposed population).*

The annual burden rose steadily from USD 4.90 billion in 2010 to a peak of USD 6.58 billion in 2014, declined to USD 5.39 billion in 2016 — coinciding with Syria conflict escalation, Yemen crisis onset, and regional economic contraction suppressing wage-based valuations — and subsequently recovered to plateau between USD 6.09 and USD 6.21 billion from 2018 through 2023. Across 252 country-year observations, direct healthcare costs showed a right-skewed distribution (mean USD 175.2 million per country-year, median USD 59.9 million), with Egypt, Algeria, Yemen, and Morocco driving regional totals. Per capita burden varied 49-fold, from USD 0.88 in Iraq (a data censoring artefact; see Methods) to USD 43.57 in Palestine.Country-level and temporal disaggregations are provided in Supplementary Figures S1.2 and S1.3.

Direct Healthcare Costs

Total direct healthcare expenditures reached USD 44.2 billion over 14 years, with intellectual disability accounting for USD 38.7 billion (87.6%) and Parkinson's disease for USD 5.5 billion (12.4%; Supplementary Figure S3, Table 2).

Table 2: Country-Level Direct Healthcare Costs

COUNTRY	14-YR DIRECT COST (USD B)	MEAN % HEALTH BUDGET	COUNTRY GROUP
Egypt	$16.26	8.4	Middle-Income
Yemen	$5.82	18.7	Conflict-Affected
Algeria	$4.99	3.3	Middle-Income
Morocco	$4.56	5.1	Middle-Income
Saudi Arabia	$3.18	0.6	Gulf/High-Income
Syria	$1.42	10.2	Conflict-Affected
Sudan	$1.39	6.4	Conflict-Affected
Tunisia	$1.35	3.3	Middle-Income
Jordan	$1.22	3.0	Middle-Income
Palestine	$0.80	4.0	Middle-Income
Libya	$0.69	1.8	Conflict-Affected
Lebanon	$0.63	1.8	Middle-Income
United Arab Emirates	$0.53	0.2	Gulf/High-Income
Oman	$0.47	1.2	Gulf/High-Income
Iraq	$0.29	0.3	Middle-Income
Kuwait	$0.29	0.4	Gulf/High-Income
Qatar	$0.14	0.2	Gulf/High-Income
Bahrain	$0.10	0.5	Gulf/High-Income

The ID component was driven by a uniform severity-weighted per-case cost of USD 6,471 per child per year applied across all countries, multiplied by attributable case counts that grew with regional population expansion. PD costs demonstrated sustained growth throughout the study period, increasing 76% from USD 329 million in 2010 to USD 579 million in 2023, driven by population ageing, improved diagnostic capacity in Gulf and middle-income states, and a uniform per-patient annual direct cost of USD 5,065 applied across all countries. The ID-to-PD cost ratio consequently narrowed from 6.9:1 in 2010 to 4.8:1 in 2023.
Country-level direct costs in 2023 exhibited 155-fold variation, from USD 7.4 million in Bahrain to USD 1.14 billion in Egypt, with the other four highest-burden countries — Yemen (USD 557M), Algeria (USD 358M),

Morocco (USD 333M), and Saudi Arabia (USD 221M) — accounting for 76% of total regional direct expenditure (Supplementary Figure S4).

The most policy-relevant expression of healthcare burden is cost as a proportion of the national health budget (Figure 2). Three distinct patterns emerged: crisis-level intensity in Yemen (escalating from 17.6% to 29.6% of national health budget between 2019 and 2023) and Sudan (9.5–14.0% sustained from 2018 onward), where pesticide-attributable neurological disease alone consumed budget shares typically allocated to entire disease categories; elevated but potentially manageable burden in Egypt (mean 8.4%, range 7.0–11.5%), Syria (volatile 5.4–15.2% with war-related spikes), and Morocco (3.8–5.9%); and low intensity in Gulf states (Qatar 0.17–0.32%, UAE 0.17–0.30%, Saudi Arabia 0.35–1.08%) and most middle-income countries (Tunisia 2.4–4.0%, Jordan 2.4–3.6%), where burden is fiscally sustainable but ethically significant. Saudi Arabia demonstrated a steady decline from 1.08% in 2010 to 0.36% in 2023, concurrent with a documented 18% reduction in national pesticide use over the same period (FAOSTAT 2021). In direct contrast, Yemen's burden ranged from 7.9% (2018, coinciding with acute economic contraction) to 29.6% (2023) of its national health budget over the study period, with a mean of 18.7% and a clear escalating trend from 2019 onward — the largest single-country contrast in the dataset. Figure S5 presents this natural experiment in full temporal resolution, illustrating how regulatory pesticide reduction and conflict-driven exposure intensification produce compounding and opposite trajectories of health budget impact over a 14-year period.

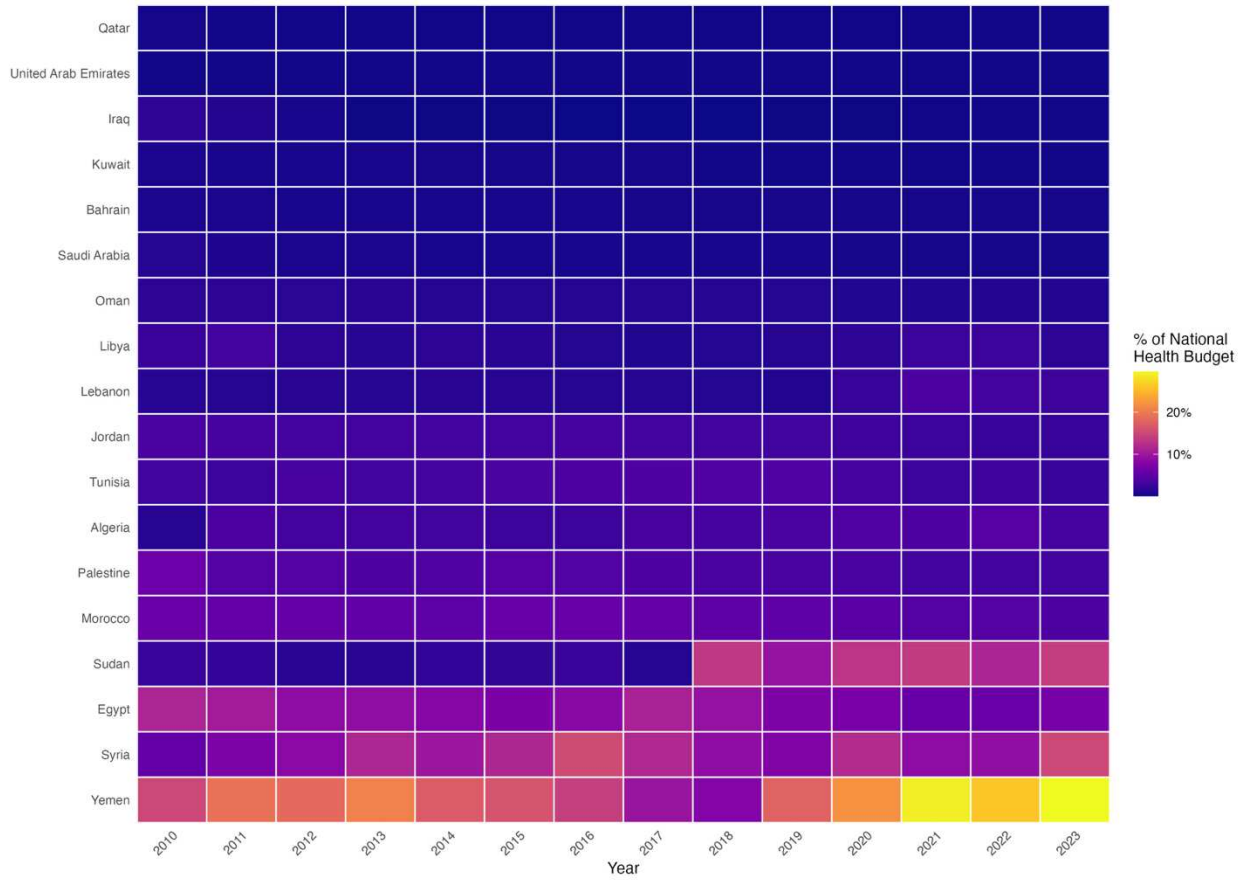


Figure 2. Direct Healthcare Costs as Percentage of National Health Budget (2010-2023). *Heatmap showing pesticide-attributable neurological disease burden intensity across 18 MENA countries and 14 years (252 country-year observations). Color scale ranges from deep purple (<0.5% of national health budget) to bright yellow (>10%). Countries ranked by 14-year average burden intensity (highest to lowest). Yemen exhibited catastrophic burden escalation 2019-2023 (18%→30% of health budget), indicating either health system collapse with budget contraction or data quality deterioration during conflict. Sudan showed concerning intensification 2018-2023 (13-14% sustained). Syria demonstrated war-related spike 2013-2016 (5%→15%), followed by partial normalization.*

Egypt maintained elevated but stable burden (7-11% throughout). Gulf states (Qatar, UAE, Iraq, Kuwait, Bahrain, Saudi Arabia, Oman) showed negligible-to-low intensity (<0.5-2.0%) reflecting large health budgets and lower disease rates. Middle-income countries (Lebanon, Jordan, Tunisia, Algeria, Palestine, Morocco) displayed sustainable moderate burden (1-6%).

Indirect Productivity Losses

Regional indirect productivity losses totalled USD 22.1 billion over 14 years, averaging USD 1.58 billion annually (range USD 1.10–1.90 billion). Reduced work capacity was the dominant component in all 18 countries, consistently exceeding 85% of total indirect burden, driven by the cumulative lifetime productivity reduction imposed by ID over 30 working years and by PD over 15 working years among the employed fraction of affected individuals. Premature mortality from PD contributed approximately 12–15% of indirect costs, constrained by the conservative assumption of mean age at death of 72 years with three remaining working years — an assumption that likely underestimates losses for occupationally exposed agricultural workers who may develop pesticide-attributable PD at younger ages (Ishihara, Cheesbrough et al. 2007). Absenteeism losses were negligible at the regional scale, below 2% of indirect totals, reflecting the small proportion of economically active cases relative to the chronic capacity-loss burden. Egypt dominated indirect costs in absolute terms (USD 6.58 billion over 14 years; 29.8% of regional total), followed by Saudi Arabia (USD 2.65 billion) and Morocco (USD 2.26 billion). Supplementary Figures S6–S8 and Table 3 provide full indirect cost decompositions by country and component.

Table 3. Country-Level Indirect Productivity Losses. Summary (2010-2023)

COUNTRY	14-YR TOTAL (USD B)	DOMINANT COMPONENT	MEAN ANNUAL (USD M)
Egypt	6.58	Mixed	$470.30M
Saudi Arabia	2.65	Reduced capacity (>85%)	$189.49M
Morocco	2.26	Premature mortality (>20%)	$161.15M
Algeria	2.08	Mixed	$148.76M
Yemen	1.44	Reduced capacity (>85%)	$102.91M
Palestine	1.10	Reduced capacity (>85%)	$78.43M
Jordan	1.03	Reduced capacity (>85%)	$73.68M
United Arab Emirates	1.01	Reduced capacity (>85%)	$71.95M
Libya	0.78	Reduced capacity (>85%)	$55.86M
Sudan	0.65	Premature mortality (>20%)	$46.49M
Tunisia	0.53	Premature mortality (>20%)	$38.17M
Oman	0.52	Reduced capacity (>85%)	$37.46M
Lebanon	0.50	Reduced capacity (>85%)	$35.43M
Kuwait	0.33	Reduced capacity (>85%)	$23.45M
Syria	0.32	Reduced capacity (>85%)	$22.81M
Qatar	0.13	Reduced capacity (>85%)	$9.24M
Bahrain	0.12	Reduced capacity (>85%)	$8.26M
Iraq	0.10	Premature mortality (>20%)	$6.98M

Intangible Quality-of-Life Costs

Under the Human Capital method, regional intangible costs totalled USD 17.2 billion over 14 years (mean USD 1.23 billion annually). Valuation framework choice was the single most consequential methodological decision, producing a 7.5-fold range: USD 1.23 billion (HC), USD 3.6 billion (WHO 1× GDP), USD 10.7 billion (WHO 3× GDP), and USD 12.4 billion (VSL). Because HC per-DALY values reflect wage disparities across MENA (USD 406 in Syria to USD 7,218 in UAE) rather than disease severity, DALY counts are used as the primary metric for cross-country comparisons throughout this analysis. Full valuation method comparisons and country-level intangible cost estimates are presented in Supplementary Figures S9–S11 and Table 4.

Table 4. Intangible Costs (HC vs. VSL Methods)

COUNTRY	HC TOTAL 14-YR (USD B)	VSL TOTAL 14-YR (USD B)	HC PER DALY (USD)
Egypt	4.88	62.32	$1,714
Saudi Arabia	2.14	22.07	$3,648
Algeria	1.56	20.86	$1,697
Morocco	1.47	32.43	$1,777
Yemen	1.24	5.56	$1,170
Palestine	0.97	1.71	$6,473
Jordan	0.91	2.33	$3,914
United Arab Emirates	0.87	2.30	$8,998
Libya	0.65	2.07	$5,079
Sudan	0.45	4.16	$1,676
Oman	0.43	3.02	$4,986
Lebanon	0.39	1.92	$3,457
Tunisia	0.36	7.26	$1,568
Kuwait	0.31	0.34	$5,549
Syria	0.25	2.35	$909
Qatar	0.12	0.16	$4,770
Bahrain	0.11	0.12	$5,458
Iraq	0.05	2.96	$1,087

Total Burden Composition and Country Rankings

Egypt ranked first in absolute 14-year economic burden (USD 27.7 billion), followed by Algeria (USD 8.64 billion), Yemen (USD 8.49 billion), Morocco (USD 8.29 billion), and Saudi Arabia (USD 7.98 billion); these five countries accounted for 73.1% of the regional total. However, absolute rankings diverged substantially from per capita rankings for 13 of 18 countries. Palestine ranked first in per capita burden (USD 43.57 per person per year) despite

ranking seventh in absolute burden, reflecting intensive pesticide application (17.3 kg per hectare versus a regional mean of 2.1 kg per hectare) concentrated over a small population. Yemen ranked first in per capita DALY rate (235 per 100,000) and second in absolute burden simultaneously — the only country requiring maximum priority under both allocation frameworks. Iraq ranked last on all metrics, a data artefact of pesticide intensity censoring rather than genuine low burden. Cost composition varied systematically by income tier and conflict status: direct healthcare costs dominated in conflict-affected countries (Syria 71.4%, Yemen 68.5%, Iraq 66.2%), while indirect productivity losses were proportionally highest in Gulf states and economically diversified middle-income countries (UAE 41.8%, Oman 36.8%, Kuwait 35.4%), and intangible costs showed the largest proportional contribution in high-wage settings where agricultural wage valuations inflate DALY monetisation (UAE 35.9%, Palestine 33.8%, Kuwait 33.3%). Full composition profiles, absolute-versus-per-capita ranking comparisons, and occupational-versus-environmental burden scatter plots are provided in Supplementary Figures S11–S13 and Table 5.

Table 5. Country Ranking by three Burden Metrics

COUNTRY	RANK: ABSOLUTE BURDEN	RANK: PER CAPITA	RANK: PER WORKER
Egypt	1	6	13
Algeria	2	13	9
Yemen	3	9	12
Morocco	4	12	16
Saudi Arabia	5	7	6
Jordan	6	3	1
Palestine	7	1	3
Sudan	8	17	17
United Arab Emirates	9	5	5
Tunisia	10	14	14
Libya	11	4	11
Syria	12	16	15
Lebanon	13	8	10
Oman	14	2	8
Kuwait	15	10	4
Iraq	16	18	18
Qatar	17	15	7
Bahrain	18	11	2

Return on Investment Analysis

Three of four modelled interventions were cost-beneficial under base-case assumptions (Figure 3, Table 6). The Surveillance System yielded the highest return, with a BCR of 11.0 (sensitivity range 7.71–14.32), a cost-effectiveness ratio of USD 651 per DALY averted (range USD 500–929), and a payback period of 0.10 years — approximately five weeks. These metrics place surveillance among the most efficient public health investments documented globally for an occupational health intervention, comparable in cost-effectiveness to childhood immunisation programmes in LMIC settings. The PPE Programme ranked second with a BCR of 3.25 (range 2.28–4.23) and CER of USD 2,796 per DALY averted (range USD 2,151–3,995). Buffer Zones ranked third with a BCR of 2.23 (range 1.56–2.90) and CER of USD 3,138 per DALY averted (range USD 2,414–4,483); the lower sensitivity bound of 1.56 remained above break-even in all scenarios, confirming robust positive returns even under pessimistic assumptions. All three interventions fell well within the WHO highly cost-effective threshold of USD

31,201 per DALY averted (1× MENA-average GDP per capita) across their full sensitivity ranges, representing 2.1%, 9.0%, and 10.1% of that threshold respectively.
The chemical ban was the sole intervention with a BCR below one (BCR 0.04, range 0.03–0.05) and a CER of USD 183,727 per DALY averted (range USD 141,328–262,467), exceeding the WHO 3× GDP ceiling of USD 93,603 under all scenario combinations. This reflects the structural mismatch between very high annual implementation costs (USD 897.8 million, dominated by farmer transition support and national enforcement infrastructure) and limited near-term health benefit (4,886 DALYs averted annually), rather than an absence of value. PD has a 15–20 year latency period, meaning the substantial disease-prevention benefit attributable to a chemical ban accrues predominantly beyond the modelled horizon and is not captured in these estimates — a recognised limitation of short-horizon cost-benefit modelling for regulatory interventions that is addressed further in the discussion. Figure S15 presents a BCR sensitivity surface across the full parameter space of assumed PD latency (5–35 years) and discount rate (0–8%) at both 20- and 35-year horizons, confirming that the chemical ban BCR does not reach 1.0 under any tested combination; even at the most optimistic inputs (5-year latency, 0% discount, 35-year horizon), the BCR reaches only 0.040, and when PD latency exceeds the modelled horizon (latency ≥ 20 years in the 20-year panel), the BCR converges to a constant floor of 0.030 because no PD benefit can accrue within that window. The directional gradient of the surface — BCR increasing toward shorter latency and lower discount rates — confirms that the chemical ban's economic case improves as the horizon extends and as the PD latency assumption is revised downward, consistent with emerging evidence that occupationally exposed agricultural workers may develop symptomatic PD earlier than the general population (Gamache, Haj Salem et al. 2019).

Corrected 20-year NPV estimates at a 4.5% discount rate were: Surveillance System USD 553 million, Buffer Zones USD 1,062 million, PPE Programme USD 171 million, and chemical ban −USD 11,198 million. Five-year NPV estimates were: Surveillance USD 187 million, Buffer Zones USD 358 million, PPE Programme USD 58 million, and chemical ban −USD 3,779 million. Supplementary Figures S16 and S17 present cost-effectiveness lollipop charts against WHO thresholds and dual-horizon NPV comparisons respectively.

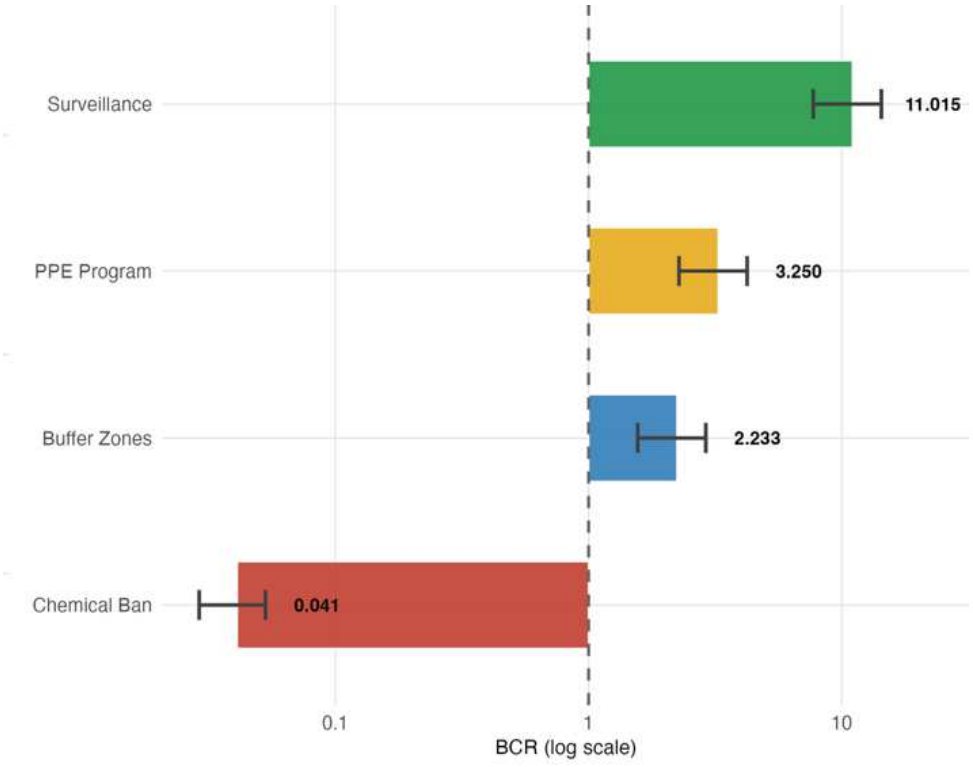


Figure 3. Benefit-Cost Ratios by Intervention Type, Typical MENA Country. *Horizontal bar chart. Log scale of four cost-beneficial interventions — Surveillance (BCR = 11.02, 95% sensitivity range 7.71–14.32), PPE Program (BCR = 3.25, range 2.28–4.23), Buffer Zones (BCR = 2.23, range 1.56–2.90), and Chemical Ban (BCR = 0.04,*

range 0.03–0.05), which falls below break-even due to high farmer transition and enforcement costs ($897.8M/year). Dashed line = break-even (BCR = 1). Error bars represent ±30% sensitivity on health impact and implementation costs. BCR = Total_Annual_Benefit_USD ÷ Annual_Implementation_Cost_USD. Human Capital valuation, 2020 USD PPP, 4.5% discount rate.

Table 6. Intervention ROI Metrics Summary

Cost-Effectiveness and WHO Classification

INTERVENTION	BCR (SENSITIVITY RANGE)	CER (USD/DALY)	WHO CLASSIFICATION
Chemical Ban	0.04 (0.03–0.05)	183727	Not cost-effective
Buffer Zones	**2.23 (1.56–2.9)**	**3138**	**Highly cost-effective**
PPE Programme	**3.25 (2.28–4.23)**	**2796**	**Highly cost-effective**
Surveillance System	**11.01 (7.71–14.32)**	**651**	**Highly cost-effective**

Tornado analysis confirmed that health impact efficacy was the dominant uncertainty driver for the three viable interventions, with BCR ranges spanning 60% of the base-case value under ±30% efficacy variation; none of these interventions approached break-even under any tested parameter combination. For the chemical ban, implementation cost was the dominant sensitivity parameter, yet even under a combined scenario of 50% cost reduction and +30% efficacy uplift — the most optimistic joint parameter combination tested — the BCR reached only 0.053, confirming that no plausible combination of cost savings and efficacy gains within the modelled horizon renders the chemical ban cost-beneficial. A pure 50% cost reduction alone, holding efficacy at base-case values, yields BCR ≈ 0.08, still well below break-even. Full tornado diagrams and scenario analysis panels are presented in Supplementary Figures S18 and S19 and Table S2.

Country Prioritisation for Policy Investment

The composite priority scoring framework, integrating absolute disease burden (40%), per capita disease rate (30%), and implementation feasibility (30%), identified six Tier 1 Urgent countries: Egypt (rank 1, composite score 13.9), Yemen (rank 2, score 13.2), Morocco (rank 3), Algeria (rank 4), Saudi Arabia (rank 5), and Jordan (rank 6), collectively accounting for 70.1% of regional disease burden (Figure 4, Table 7). Egypt's top ranking reflects the highest absolute burden in the region (203,275 DALYs annually, 35.8% of MENA total) combined with moderate-to-high implementation feasibility (health system capacity index 60/100, policy readiness rated medium). Yemen ranked second despite the lowest feasibility score in the region (1/5, capacity index 15/100) because of the highest per capita disease rate (235 DALYs per 100,000), illustrating that extreme per capita burden can override feasibility constraints in composite scoring; realistic implementation in Yemen would require emergency humanitarian channels rather than conventional government programme delivery.

The burden-feasibility matrix revealed three clusters: Egypt, Morocco, Tunisia, and Saudi Arabia (high burden, high feasibility — optimal targets with 4–6 year programme timelines); Yemen, Algeria, and Sudan (high burden, constrained feasibility — requiring mobile surveillance and NGO-led delivery); and Gulf states (low burden, high feasibility — cost-effective rapid wins for expatriate agricultural workforces at USD 1.4–14.2 million over five years). The surveillance system was identified as the highest ROI intervention for all 18 countries based on regional-average modelling (BCR 11.0). Estimated five-year implementation costs scaled substantially with agricultural workforce size, ranging from USD 1.4 million (Bahrain, 8,600 workers) to USD 917.6 million (Egypt, 4.9 million workers), with cost per DALY averted ranging from USD 42 (Bahrain) to USD 28,136 (Egypt) — all below the WHO highly cost-effective threshold. Iraq ranked last (rank 18, composite score 2.8), reflecting both data censoring artefacts suppressing apparent burden and genuine implementation barriers in a conflict reconstruction context (capacity index 35/100). Country-specific primary intervention recommendations, and five-year cost and impact projections are provided in Table 7 and Supplementary Figure S20 and S21. Figure S22 presents the recommended

intervention sequencing for all 18 MENA countries across the three priority tiers, derived from the integrated BCR, payback period, and feasibility analysis. Across all tiers, the Surveillance System is recommended as the first-step intervention, followed sequentially by PPE Programme and Buffer Zones; the chemical ban is designated a long-horizon regulatory target consistent with its PD latency profile. Yemen's retention in Tier 1 despite the lowest feasibility score reflects its extreme per capita DALY rate; implementation would require emergency humanitarian channels (Figure S22).

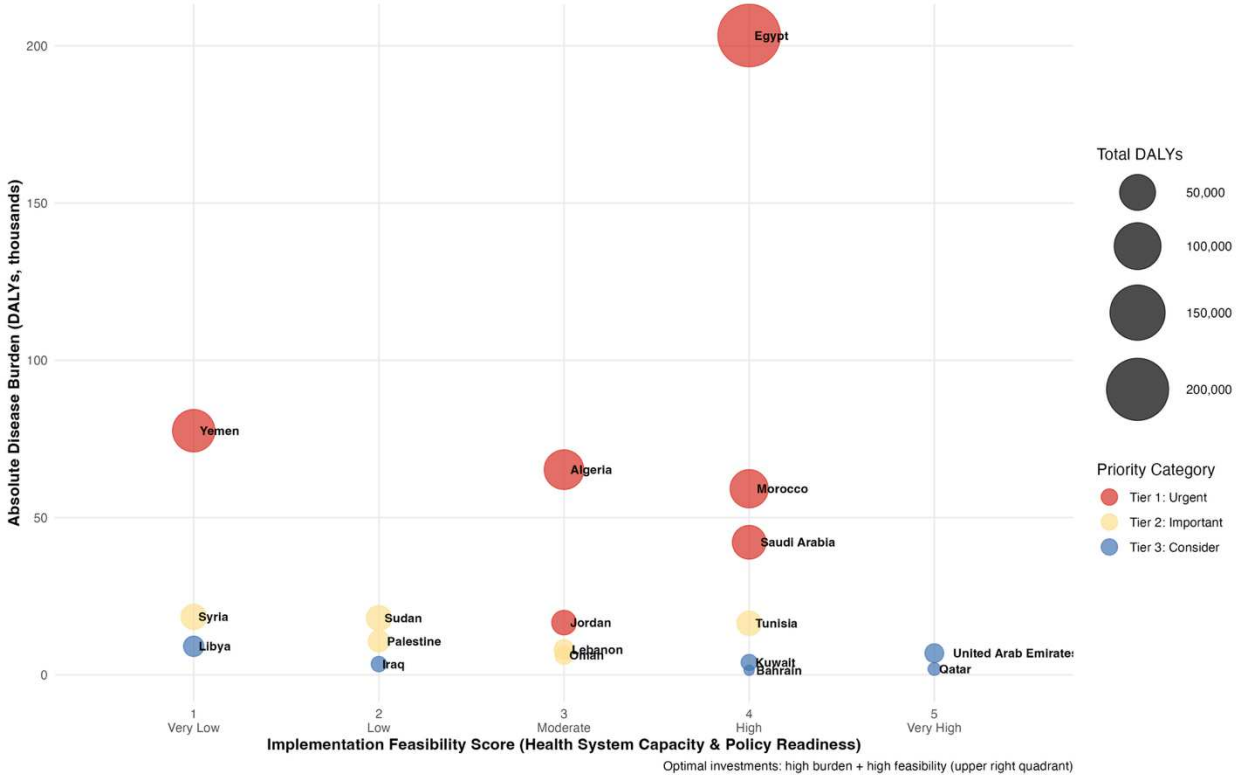


Figure 4. Country prioritization matrix: disease burden versus implementation feasibility. *Bubble chart positions each MENA country by implementation feasibility score (x-axis, 1=very low to 5=very high) and absolute disease burden (y-axis, thousands of DALYs). Bubble size represents total DALYs; color indicates priority tier (red=Tier 1 Urgent, yellow=Tier 2 Important, blue=Tier 3 Consider). Optimal investment opportunities appear in the upper-right quadrant (high burden + high feasibility): Egypt, Morocco, and Saudi Arabia. Yemen occupies the upper-left quadrant (high burden, very low feasibility) due to active conflict. Gulf states (UAE, Qatar, Kuwait, Bahrain) cluster in the lower-right quadrant (low burden, high feasibility) reflecting small agricultural sectors and advanced health systems. Syria and Libya show low feasibility (conflict settings) with moderate burden.*

Table 7. Country Prioritisation Tiering

COUNTRY	PRIORITY TIER	RECOMMENDED INTERVENTION	5-YR COST (USD MILLION)
Egypt	Tier 1 — Urgent	Surveillance System	917.6
Yemen	Tier 1 — Urgent	Surveillance System	279.7
Morocco	Tier 1 — Urgent	Surveillance System	600.5
Algeria	Tier 1 — Urgent	Surveillance System	182.4
Saudi Arabia	Tier 1 — Urgent	Surveillance System	51.8
Jordan	Tier 1 — Urgent	Surveillance System	9.8
Palestine	Tier 2 — Important	Surveillance System	11.5
Tunisia	Tier 2 — Important	Surveillance System	84.9
Syria	Tier 2 — Important	Surveillance System	79.1
Oman	Tier 2 — Important	Surveillance System	16.0
Lebanon	Tier 2 — Important	Surveillance System	41.0
Sudan	Tier 2 — Important	Surveillance System	713.0
Libya	Tier 3 — Consider	Surveillance System	59.4
United Arab Emirates	Tier 3 — Consider	Surveillance System	14.2
Kuwait	Tier 3 — Consider	Surveillance System	6.5
Bahrain	Tier 3 — Consider	Surveillance System	1.4
Qatar	Tier 3 — Consider	Surveillance System	3.7
Iraq	Tier 3 — Consider	Surveillance System	285.8

Discussion

This study provides, to our knowledge, the first comprehensive economic quantification of pesticide-attributable neurological disease burden across 18 MENA countries over a 14-year period, estimating a total regional cost of USD 83.4 billion from 2010 to 2023. This figure scale exceeds the entire annual health expenditure of Egypt, Morocco, and Algeria combined (WDI 2026), and yet it almost certainly represents an underestimate given the conservative valuation framework adopted, the exclusion of intergenerational effects, and the near-complete absence of MENA-specific cost-of-illness data on which to base direct estimates.

The dominance of intellectual disability in the overall cost structure — accounting for 87.6% of direct healthcare expenditures and the vast majority of DALYs — reflects a fundamental but underappreciated asymmetry in the pesticide-neurological disease relationship in MENA. Organophosphate pesticides are well-established developmental neurotoxicants, and LMIC reviews also identify carbamates among pesticide classes consistently associated with worse neurodevelopmental outcomes. The LMIC literature links prenatal and early-childhood exposure to poorer cognitive and behavioral development, reduced IQ, and developmental delay, while a recent GBD-based analysis of IDII burden reported that 85% of global IDII DALYs were concentrated in South Asia and North Africa/Middle East, where children are exposed to multiple simultaneous neurotoxic pressures and where mitigation infrastructure is weakest (Hertz-Picciotto, Sass et al. 2018, Coleman, Asad et al. 2025, Liu, Zhang et al. 2025). Our findings operationalise this burden economically for the first time in the MENA context, showing that the neurodevelopmental pathway — driven by environmental and gestational exposure rather than direct occupational contact — is the economically dominant mechanism in the region, not PD. This has direct implications for intervention targeting: purely occupational safety approaches such as PPE programmes, while valuable, cannot capture the majority of attributable burden because they do not address the environmental pathway through which pregnant women and young children are exposed. Buffer zones, which directly reduce residential and peri-agricultural drift exposure, may therefore have greater population-level economic value than occupational interventions alone, despite their lower BCR in our model, because our model conservatively attributed only 35% ID risk reduction to buffer zones. Reviews and cohort studies show higher pesticide exposure among residents living closer to agricultural land and lower exposure with increasing distance (Coronado, Holte et al. 2011, Dereumeaux, Fillol et al. 2020, Suarez-Lopez, Nazeeh et al. 2020).

The temporal trajectory of PD costs — growing 76% from 2010 to 2023 — is consistent with global and regional trends in PD epidemiology. The age-standardised point prevalence of PD in MENA increased by 15.4% from 1990 to 2019 (Safiri, Noori et al. 2023), and global modelling studies project that PD prevalence will more than double by 2050, driven primarily by population ageing (Su, Cui et al. 2025). In MENA specifically, the proportion of the

population aged 60 years and above is projected to rise from approximately 7% in 2023 to over 15% by 2040, creating a compounding dynamic: the agricultural workforce that accumulated decades of organophosphate exposure during the 1980s, 1990s, and 2000s is now ageing into the peak PD risk window, and the healthcare costs of that long-latency burden are only beginning to materialise. Our model's use of a fixed age at death of 72 years with three remaining working years to calculate premature mortality losses was deliberately conservative; the true productivity cost of pesticide-attributable PD in occupationally exposed agricultural workers, who may develop symptomatic disease a decade earlier than the general population (Gamache, Haj Salem et al. 2019), is likely substantially higher. This means that indirect costs, already comprising 26.5% of our total burden estimate, are probably the most underestimated component in the entire analysis.

Perhaps the most striking single finding is Yemen's position: the second-highest absolute burden in the region and the highest per capita DALY rate (235 per 100,000), despite possessing the most severely degraded health system (United-Nations 2024) and the lowest healthcare expenditure per capita of any country we studied. This paradox is not contradictory — it is epidemiologically coherent. Yemen combines sustained high fertility (4.2 births per woman in 2023) (WB 2024, WB 2025), continued agricultural pesticide use despite the collapse of regulatory oversight, and a population of predominantly rural smallholders with minimal protective infrastructure (WB 2025). The economic cost estimate of USD 8.49 billion over 14 years for Yemen is almost certainly a conservative lower bound, given that health system collapse means a large proportion of cases are never diagnosed, costed, or counted. The GBD-consistent epidemiological burden data on which this study rests are themselves derived partly from modelled estimates for conflict years, and the true disease burden in Yemen is plausibly higher than any modelled figure can capture (Darwish, Samy et al. 2026). What is clear is that the framing of Yemen's pesticide-neurological burden purely as a conflict-related problem — to be addressed after peace is restored — is not defensible on either epidemiological or economic grounds. Humanitarian pesticide safety interventions, particularly emergency PPE distribution and community-level buffer enforcement, could be implemented through existing aid corridors and would represent genuinely cost-effective investments even within a fragile-state context.

The contrast between Yemen and Saudi Arabia is instructive. Saudi Arabia demonstrated a steady decline in its healthcare budget share attributable to pesticide-neurological disease, from 1.08% in 2010 to 0.36% in 2023, concurrent with an 18% documented reduction in national pesticide use over the same period. This is one of the few observable natural experiments in the MENA dataset that suggests a directional relationship between regulatory action and economic burden relief, even if causal attribution requires caution given the many confounders operating over a 14-year horizon. Gulf states more broadly showed the lowest burden intensity relative to national health budgets, reflecting not only smaller agricultural sectors but also more functional pesticide regulatory frameworks and occupational safety infrastructure. The lesson is not that Gulf states face no problem — their expatriate agricultural workforces carry meaningful per-worker burden — but rather that the structural conditions for effective intervention already exist in these settings, and the investment required is comparatively modest.

Egypt's dominant position across almost every absolute burden metric is unsurprising given its population size and agricultural intensity, but it deserves specific attention for a reason that goes beyond scale. Egypt's pesticide-neurological disease burden consumed a mean 8.4% of its national health budget annually over 14 years.

For context, most LMIC health systems allocate approximately 2% of health budgets to all mental health conditions combined (EMRO 2015); pesticide-attributable neurological disease alone may match or exceed this share in Egypt (mean 8.4%), Sudan (mean 6.4%), and Yemen (mean 18.7%) — resources unavailable for other health priorities.

Palestine's consistently anomalous per capita metrics — first in per capita economic burden, second in per capita DALY rate — reflect a genuinely distinctive agricultural intensity situation rather than a data artefact. With pesticide application rates of 17.3 kg per hectare, approximately eight times the regional mean, in a territory where over a quarter of the population is rural and where spatial constraints mean agricultural land and residential areas are geographically inseparable, Palestine represents a case where the occupational and environmental exposure pathways merge almost entirely. This observation reinforces the argument: the countries requiring comprehensive multi-component interventions — addressing both occupational and residential pathways simultaneously.

The ROI analysis was used to produce a decision-stable investment hierarchy. The Surveillance System's BCR of 11.0 and CER of USD 651 per DALY averted make it look like an obvious first choice, and operationally it probably should be — the MENA region has almost no functional pesticide biomonitoring or neurological disease registry infrastructure, and without surveillance data, neither the scale of the problem nor the effect of interventions can be measured. However, surveillance alone prevents no exposure. It creates the evidence base from which other interventions are justified and targeted. Its high BCR reflects the combination of very low implementation cost and meaningful downstream health impact through policy-enforcement pathways, but this indirect pathway requires political will and institutional linkage that cannot be assumed. The WHO global assessment of pesticide lifecycle management found that low-income countries had the most gaps in pesticide legislation and enforcement, with

inadequate surveillance being a near-universal feature (van den Berg, Gu et al. 2020). Establishing surveillance without simultaneously building the regulatory and enforcement capacity to act on its findings would yield only the direct clinical benefit component — estimated at 5% risk reduction rather than the 10% modelled here — halving the BCR to approximately 5.5 and more than doubling the CER to approximately USD 1,300 per DALY. This remains cost-effective but illustrates that the surveillance BCR is conditional on governance quality in a way that the other interventions are not.

The Chemical Ban's BCR of 0.04 within the modelled horizon should not be read as evidence that banning organophosphates and carbamates is economically irrational. It is evidence that short-horizon cost-benefit analysis systematically disadvantages regulatory interventions with long latency periods. The 15–20 year lag between occupational pesticide exposure and clinically manifest PD means that a ban implemented today would generate its primary PD prevention benefit in the 2040s and 2050s — well beyond the 5- and 20-year modelling windows used here. Natural experiments following organophosphate bans in Sri Lanka and several European countries demonstrated large reductions in poisoning burden within 12–36 months, confirming that regulatory interventions do work (Gunnell, Eddleston et al. 2007, Knipe, Gunnell et al. 2017); the economic return from neurological disease prevention simply happens too slowly to appear in conventional health economic timeframes. A 35-year NPV calculation incorporating the latency-adjusted PD prevention benefit would almost certainly yield a positive return for the chemical ban in most MENA countries, particularly in Egypt, Morocco, and Algeria where pesticide intensity and disease burden are simultaneously high and regulatory capacity is feasible.

Several limitations of this study must be acknowledged. The absence of MENA-specific cost-of-illness data for either ID or PD is the most fundamental constraint. The per-case cost estimates used — USD 6,471 for ID and USD 5,065 for PD, applied uniformly across all 18 countries — were derived from Australian and Chinese source data respectively, with contextual adaptation based on healthcare spending benchmarks. While these represent the best available LMIC-comparable estimates, they cannot capture the heterogeneity of actual care-seeking behaviour, out-of-pocket expenditure patterns, or informal caregiving costs across countries as different as Qatar and Sudan. The uniform per-case cost approach likely overestimates costs in settings with limited diagnostic access (where many cases go undetected and untreated) and underestimates them in settings where families bear catastrophic out-of-pocket costs in the absence of social protection. The disability-poverty cycle documented— where disability generates poverty, which reduces access to care, which worsens functional outcomes, which deepens poverty — operates powerfully in MENA LMIC settings but is not captured in any component of our cost estimates (Banks, Kuper et al. 2017). The Human Capital valuation method's use of agricultural wages as the DALY proxy produces per-DALY values ranging from USD 406 in Syria to USD 7,218 in the UAE — a 17-fold spread that reflects wage inequality rather than differential severity of neurological disease. This means that identical interventions preventing identical numbers of DALYs will generate far higher monetised benefits in the UAE than in Syria under our framework, potentially distorting cross-country resource allocation decisions toward wealthier settings. Decision-makers should use DALY counts, not monetised burden, as the primary equity-sensitive metric for cross-country comparisons.

Finally, this analysis does not capture the full economic burden of pesticide-attributable neurological disease. Costs excluded from the model include: soil and water remediation costs; intergenerational effects of in-utero exposure on subsequent birth cohorts; economic costs of social exclusion and reduced educational attainment in children with pesticide-attributable ID; the indirect productivity losses of family members who reduce labour force participation to provide informal care; and the substantial but unquantifiable psychological costs borne by caregivers. Including these components would substantially increase all burden estimates. The USD 83.4 billion regional total over 14 years is therefore a lower bound, and the true economic case for pesticide regulation in MENA is stronger than our figures can convey.

Declarations

Ethics Approval and Consent to Participate

This study is based exclusively on publicly available, aggregate-level secondary data obtained from international and national repositories (World Bank DataBank, ILOStat, FAOSTAT, Global Burden of Disease Study outputs, and published cost-of-illness literature). No primary data collection involving human participants, human tissue, or animal subjects was conducted. Accordingly, ethics committee approval and informed consent procedures were not applicable to this research.

Consent for Publication

Not applicable. This study does not contain data from any individual person.

Author Contributions

Author contributions are reported according to the CRediT (Contributor Roles Taxonomy) framework:

- Aya Darwish (AD): Conceptualization; Methodology; Investigation; Writing – Original Draft; Writing – Review & Editing; Validation.
- Aya Samy (AS): Conceptualization; Methodology; Formal Analysis; Investigation; Writing – Original Draft; Writing – Review & Editing; Validation.
- Ahmed Amin (AA): Investigation; Resources; Writing – Review & Editing; Validation.
- Jana Al-Nady (JA): Investigation; Resources; Writing – Review & Editing; Validation.
- Shimaa Sami (SS): Investigation; Resources; Writing – Review & Editing; Validation.
- Moustafa Sherif (MS): Conceptualization; Methodology; Formal Analysis; Data Curation; Writing – Original Draft; Writing – Review & Editing; Visualization; Project Administration; Funding Acquisition; Supervision.

AD and AS contributed equally and share first authorship. All authors have read and approved the final version of the manuscript.

Funding

This research was supported by the Pathfinder Epidemiology Academy, Egypt (Grant Number: PAF1544i). The funding body played no role in the design of the study, data collection, analysis or interpretation of results, or in the preparation, review, or decision to submit this manuscript for publication.

Data Availability Statement

This study did not generate or deposit primary datasets. All data used in this analysis were derived from publicly accessible secondary sources. Macroeconomic parameters were obtained from the World Bank DataBank (https://databank.worldbank.org). Agricultural wage series were retrieved from ILOStat (https://ilostat.ilo.org). Pesticide use and trade statistics were sourced from FAOSTAT (https://www.fao.org/faostat). Epidemiological burden estimates underpinning the economic calculations were derived from the companion analysis (Darwish, Samy et al. 2026). Healthcare cost parameters were identified through a systematic literature search of 36 peer-reviewed cost-of-illness studies. All data sources, imputation procedures, and quality flags are described in Supplementary Table S1. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Appendix A. Supplementary data

Supplementary data associated with this article — including Supplementary Tables S1–S2, and Supplementary Figures S1–S22 — can be found in the online version of this article at the publisher's website. Supplementary material is also available from the corresponding author upon request.

Competing Interests

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

Acknowledgments

The authors gratefully acknowledge financial support from the Pathfinder Epidemiology Academy (Egypt) through Grant 25PAF1544i. We acknowledge the Food and Agriculture Organization of the United Nations (FAO/FAOSTAT), the World Bank (World Development Indicators DataBank), the United Nations Population Division, the International Labour Organization (ILOStat), and the Institute for Health Metrics and Evaluation (IHME/Global Burden of Disease Study) for providing the publicly accessible datasets on which this analysis was built.

Clinical trial number

not applicable.

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