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OPTIMIZATION MODELS FOR EQUITABLE RESOURCE ALLOCATION IN PUBLIC HEALTH SYSTEMS: A SYSTEMATIC REVIEW OF METHODS AND OUTCOMES

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ABSTRACT

Public health resource allocation often relies on optimization models that prioritize efficiency, yet these approaches may reproduce existing inequities if fairness is not formally incorporated. This review examined how equity and fairness have been embedded within mathematical optimization models used for public health resource allocation in the United States and other high-income settings. We conducted a systematic review of peer-reviewed studies published between January 2021 and June 2026. Eligible studies applied formal optimization methods and embedded a quantifiable equity or fairness metric directly into the model structure. Because of substantial heterogeneity in model types, equity definitions, and public health domains, findings were synthesized narratively. Twenty-nine studies met inclusion criteria. Mixed-integer linear programming and stochastic programming were the most frequently used architectures, followed by linear, dynamic, nonlinear, and hybrid predictive-prescriptive models. Equity was operationalized in three main ways: as a structural constraint, as a co-objective, or as a parameter within the objective function. Across studies, equity constraints often improved access for underserved groups and, in many cases, produced modest or no efficiency penalties. Trade-offs were most apparent in severely scarce pandemic settings, while several chronic disease, emergency care, and infrastructure allocation studies found that equity and efficiency could be mutually reinforcing. Equity-explicit optimization is technically feasible across multiple public health applications and can often improve fairness without substantial operational compromise. The findings support broader use of optimization models that incorporate fairness directly into allocation decisions, particularly when historical inequities have shaped existing systems.

Keywords: Resource allocation, Optimization models, Health equity, Fairness, Public health systems

1 INTRODUCTION

Public health systems in the United States experience persistent structural challenges. Resources such as vaccines, hospital beds, screening capacity, and outreach staff are limited. The populations requiring these resources are unevenly distributed and possess unequal access or ability to benefit from them. The Centers for Disease Control and Prevention (CDC) defines health equity as ensuring that everyone has a fair and just opportunity to attain their highest level of health (Centers for Disease Control and Prevention [CDC], 2024). Achieving health equity depends significantly on resource allocation, as unequal access to care is a primary driver of health disparities (Asamani et al., 2021). Despite

this commitment, international benchmarks indicate that the United States consistently underperforms relative to other high-income countries on equity measures. These disparities are particularly evident in financial barriers, limited access outside standard hours, and variations in patient experiences (Blumenthal et al., 2024). The persistent gap between equity goals and actual outcomes has prompted researchers in public health, health services research, and operations research to consider a critical question: Can resource allocation decisions be formally modeled to embed equity directly within the mathematical framework, rather than treating it as secondary to efficiency?

The COVID-19 pandemic transformed this theoretical question into an urgent practical challenge. Between 2020 and 2021, vaccine doses, therapeutics, and personal protective equipment were severely limited. Allocation decisions became fundamentally distributive, producing uneven effects across demographic groups. During this period, entrenched systemic inequities resulted in higher rates of infection, hospitalization, and mortality among Black, Indigenous, and People of Color in the United States (Tai et al., 2022). In response, an expanding body of literature began to employ formal mathematical optimization for equitable distribution, moving beyond reliance on policy analysis alone. For instance, some models incorporated age- and race-stratified transmission dynamics to evaluate vaccine allocations that targeted inequities in outcomes while also minimizing mortality (Stafford et al., 2023). A key insight from this period is that, under resource scarcity, a clear trade-off often exists between minimizing disease burden and reducing inequity (Asamani et al., 2021). Equity is therefore rarely cost-free; rather, it is a distinct and competing objective that must be explicitly defined and balanced.

This insight is well-developed in operations research, even though its translation into public health practice is more recent. Methodologists formalized the efficiency–fairness trade-off over a decade ago through foundational work on resource allocation problems (Bertsimas et al., 2012), and that work has been adapted to healthcare settings such as organ allocation for transplantation (Bertsimas et al., 2013). Scoping reviews of operations research in global health have similarly identified equity and societal impact as recurring themes that have historically been inconsistently operationalized across the mathematical literature (Bradley et al., 2017). These research threads share an explicit reliance on formal mathematical structures, including linear, integer, stochastic, multi-objective, and dynamic programming, as well as simulation-optimization frameworks. These structures encode fairness criteria directly into a model's constraints or objective function rather than evaluating equity metrics after allocation decisions are executed.

Despite this methodological sophistication, the literature remains fragmented along lines that matter for U.S. public health translation. Existing systematic reviews specialize narrowly within isolated domains. Some synthesize optimization models for specific infectious diseases such as HIV/AIDS but focus on geographies without offering a cross-domain view of public health infrastructure (Avanceña & Hutton, 2020).

Others systematically review methods for eliciting equity–efficiency trade-offs but emphasize preference-based economics and cost-effectiveness analysis rather than constrained mathematical optimization architectures. Still others review pandemic-era resource allocation broadly but do not require that an explicit, quantifiable equity metric be mathematically embedded in the model itself. These reviews frequently include papers where equity is discussed only qualitatively (Wang et al., 2024). To date, no systematic review has isolated the precise intersection of formal optimization models applied to systemic constraints of U.S. or transferable high-income public health infrastructures that embed an explicit equity or fairness metric directly into the model's formulation.

This gap has significant practical and academic consequences. U.S. public health agencies operate under decentralized, fragmented, and chronically resource-constrained conditions at the federal, state, and local levels (National Network of Public Health Institutes, 2021). Decisions about where to site mobile testing clinics, how to distribute stockpiled countermeasures, or how to deploy community health workforces carry immediate equity implications. Without a consolidated and rigorous synthesis of which optimization methods have been successfully deployed, how equity has been operationalized within those models, and what outcomes they yielded when evaluated or implemented, policymakers and applied researchers must navigate scattered domain-specific literature rather than a coherent evidence-based framework.

This systematic review directly addresses that gap. We synthesize peer-reviewed literature published between January 2021 and June 2026 that applies formal mathematical optimization techniques, including linear, integer, stochastic, multi-objective, dynamic programming, and simulation optimization, to resource allocation challenges within U.S. public health systems or other high-income country contexts with demonstrated structural transferability to U.S. infrastructure. In strict alignment with our protocol, we restrict inclusion to studies that embed an explicit equity or fairness metric directly into the model's structural formulation. This includes a fairness constraint in the objective function, a minimum coverage threshold for an explicitly defined vulnerable population, or a mathematical disparity-reduction target. This review aims to map the methodological landscape of equity-explicit optimization in public health, identify which operationalizations and optimization architectures have been most applied and to what populations, and surface critical methodological and translational gaps to guide future model development and health policy implementation.

2 METHODS

2.1 Study Design

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). The primary objective was to synthesize empirical evidence on mathematical optimization models for resource allocation in public health systems, with a focus on the formal integration of equity and fairness metrics within these models. Due to substantial heterogeneity in model architectures, decision variables, and objective functions across the operational research literature, statistical pooling was not feasible. Therefore, a qualitative narrative synthesis was employed, and meta-analysis was not conducted. The review protocol was not publicly registered.

2.2 Search Strategy

A comprehensive electronic search was conducted in PubMed and Scopus to identify literature published between January 2021 and June 2026. Search strategies combined controlled vocabulary terms, such as Medical Subject Headings (MeSH) in PubMed, with free-text terms in titles, abstracts, and keywords. The search was structured around four core pillars: resource allocation, mathematical optimization, equity metrics, and public health settings.

Representative keywords included *"resource allocation," "vaccine allocation," and "rationing" for the resource domain; "linear programming," "integer programming," "stochastic programming," "dynamic programming," "simulation optimization," "mathematical model," and "operations research" for optimization methods; "health equity," "health disparities," "fairness," "underserved," "vulnerable population," "Gini," "disparity reduction," and "inequity" for equity; and "public health," "healthcare," "hospital," "vaccination," "epidemic," "pandemic," and "community health"* for public health. Searches were limited to English-language, peer-reviewed journal articles. Complete search strings are available from the corresponding author upon request.

Records retrieved from both databases were exported to Zotero reference management software (version 7.0) for automated and manual deduplication before initial title and abstract screening. To supplement the primary database searches and ensure literature saturation, citation chasing was performed on the final set of included articles using Google Scholar. This process included backward citation searching by reviewing reference lists of included studies and forward citation searching using Google Scholar's citation indexing to identify more recent publications citing the included papers. Candidate records identified through citation tracking were manually logged and cross-referenced in Zotero to eliminate redundancy.

2.3 Screening and Study Selection

All unique records remaining after deduplication underwent initial title and abstract screening against predefined eligibility criteria, followed by full-text review of studies advancing past the initial screening. Two independent reviewers conducted screening at both stages, resolving discrepancies through discussion until consensus was reached.

Eligibility criteria required studies to meet several benchmarks. Inclusion was limited to peer-reviewed journal articles published in English between January 2021 and June 2026. Studies had to be set within public health or healthcare systems in the United States or other high-income countries, including the United Kingdom, Canada, Australia, and European Union member states, provided that any non-U.S. optimization framework was explicitly transferable or adaptable to U.S. healthcare infrastructure. Methodologically, only studies applying formal mathematical or constrained optimization techniques, specifically linear, integer, stochastic, multi-objective, or dynamic programming, as well as algorithmic simulation optimization, were included. Each study was also required to incorporate a quantifiable equity or fairness metric directly into the model structure, operationalized as a fairness constraint in the objective function (such as a Gini coefficient, min-max fairness principle, or Lorenz curve), a minimum coverage or access threshold for a vulnerable or underserved population (including racial or ethnic minorities, rural communities, low-income groups, or the uninsured), or an explicit mathematical disparity-reduction target embedded in the model architecture.

Exclusion criteria were systematically applied to filter out irrelevant literature. Studies were excluded if published prior to January 2021 or set exclusively in low- and middle-income country contexts without demonstrated transferability to U.S. settings. Designs relying solely on descriptive or inferential statistics, qualitative frameworks, narrative reviews, or standard cost-effectiveness analyses lacking an embedded optimization algorithm were omitted. Standalone machine learning or predictive models were excluded unless directly coupled with a formal constrained optimization component. Models optimizing solely for operational efficiency, cost minimization, throughput, or capacity maximization were excluded even if equity or fairness was discussed qualitatively. Dissertations, theses, editorials, book chapters, grey literature, and preprints were also excluded unless a peer-reviewed publication could not be identified and the study demonstrated exceptional methodological relevance.

2.4 Data Extraction

A standardized, pilot-tested data extraction matrix was used to systematically compile data from each included study. Extracted fields included primary author(s) and year of publication, geographic setting, target population characteristics, and the specific optimization method. The extraction also tracked the equity metric and its formal mathematical operationalization, the public health domain or application area, and the primary operational findings. For studies outside the United States, an additional field documented the structural mechanisms validating the model's transferability to U.S. infrastructure. All extracted data were independently cross verified by both reviewers for accuracy and consistency.

2.5 Data Synthesis

In accordance with the Synthesis Without Meta-analysis (SWiM) reporting guidelines, a narrative synthesis approach was used to analyze and integrate findings across the final corpus (Campbell et al., 2020). Included studies were grouped and compared across three primary dimensions: the underlying mathematical optimization architecture, the formal operationalization of the equity metric, and the specific public health application domain. Within each thematic cluster, studies were critically evaluated for methodological patterns, convergences, and divergences in outcomes. This structured comparison aimed to map the current state of equity-explicit optimization in public health resource allocation and to identify critical gaps in model translation and policy implementation.

3 RESULTS

3.1 Study Selection

The systematic search and screening process yielded a structured pipeline of records from initial identification to final study inclusion. Database searches across PubMed (n = 585) and Scopus (n = 824), supplemented by targeted forward and backward citation chasing conducted in Google Scholar (n = 41), generated a raw total of 1,450 records. These records were compiled within Zotero reference management software (version 7.0) for processing. Following automated deduplication, 103 duplicate records were removed. An additional 790 records were marked as ineligible through automated screening tools prior to title and abstract review, yielding 557 unique records to undergo manual eligibility screening.

The 557 unique records were subjected to rigorous title and abstract screening against the predefined eligibility criteria. This phase excluded 483 records that failed to meet fundamental protocol requirements, including studies focused exclusively on low- and middle-income country contexts without structural transferability to U.S. or other high-income settings, studies relying solely on descriptive statistics or qualitative frameworks without an embedded optimization engine, and studies that did not address public health resource allocation in any substantive form. This initial screening gate advanced 74 records to full-text eligibility assessment, all of which were successfully retrieved for review.

Full-text articles for all 74 candidate studies were retrieved and subjected to independent, comprehensive evaluation by two reviewers. During this detailed assessment, 45 studies were systematically excluded based on specific protocol violations. The primary drivers of full-text exclusion were: models that optimized entirely for operational throughput or cost minimization without formalizing a mathematical equity metric in the model structure; standalone predictive, machine learning, or reinforcement learning frameworks not directly coupled with a constrained optimization architecture; papers in which equity was discussed solely as a qualitative narrative rather than a structurally embedded mathematical parameter; geographic settings confirmed as low- or middle-income upon full-text review; and algorithmic or heuristic frameworks that did not qualify as formal mathematical optimization under the protocol definition. Discrepancies between reviewers at both screening stages were resolved through structured discussion until consensus was reached. This multi-stage process ultimately yielded a final corpus of 29 peer-reviewed articles meeting all eligibility criteria for inclusion in the qualitative narrative synthesis. The complete study selection flow is presented in **Fig 1** in accordance with PRISMA 2020 reporting requirements.

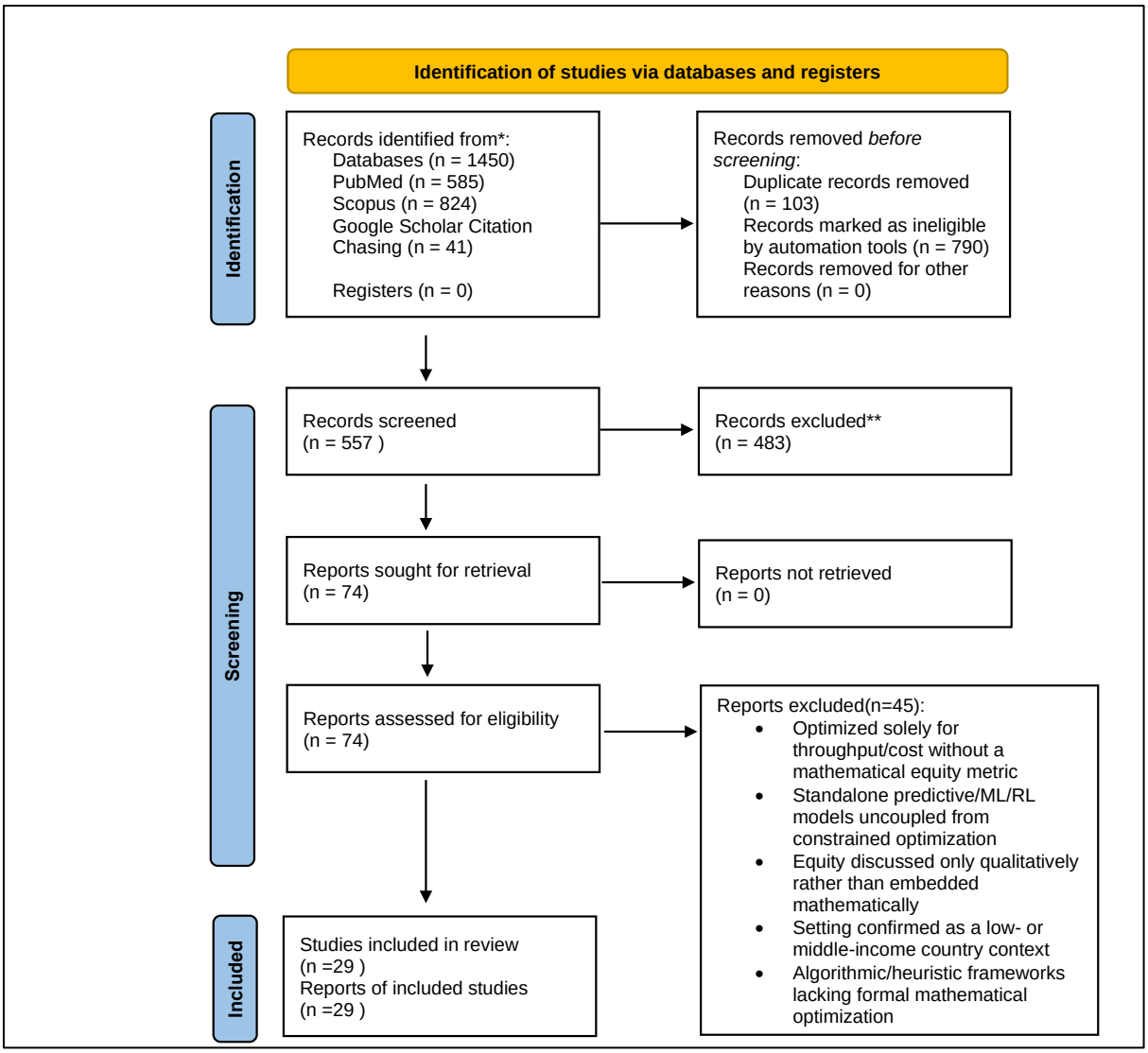


Figure 1: Prisma 2020 flow diagram

3.2 Characteristics of Included Studies

The 29 included studies were published between 2021 and 2026 and collectively span eight high-income country settings. The United States accounted for most of the corpus, with 22 studies situated in domestic public health or healthcare delivery contexts. The remaining seven studies were conducted in the United Kingdom (n = 2), Austria (n = 1), Canada (n = 1), France (n = 1), Portugal (n = 1), and two additional studies addressing theoretically generalizable high-income country frameworks without a single national application. The geographic concentration in U.S. settings reflects both the review's primary focus and the disproportionate volume of equity-explicit optimization research produced within U.S. academic and public health institutions, particularly following the COVID-19 pandemic. Table 1 presents the full data extraction matrix for all 29 studies.

Across the corpus, six broad public health application domains were represented. Vaccine and pandemic resource allocation constituted the largest cluster, encompassing 15 studies that addressed COVID-19 vaccine distribution, testing kit allocation, emergency supply rationing, or immunization facility siting (Bui et al., 2024; Stafford et al., 2023; Sengul Orgut et al., 2023; Thul & Powell, 2023; Bertsimas et al., 2022; Kim et al., 2025; Barth et al., 2024; Manshadi et al., 2023; Mohammadi et al., 2024; Li et al., 2025; Basciftci et al., 2023; Erdogan et al., 2024; Gutjahr, 2023; Gutjahr, 2026; Anderson et al., 2025). Chronic and non-communicable disease management contributed five studies covering hepatitis C treatment, opioid settlement allocation, diabetes care, and preventive dental health (Han et al., 2021; Chen et al., 2025; Mukherjee et al., 2025; Ma et al., 2023; Cheong, 2026). Emergency services and acute care accounted for four studies addressing ambulance planning, emergency department placement, chemotherapy shortage triage, and post-disaster mental health resource deployment (Abreu et al., 2025; Canellas et al., 2025; Hantel et al., 2022; Cunningham et al., 2021). Two studies addressed HIV resource allocation in the context of fairness-aware frameworks (Bowring et al., 2024; Akbari-Moghaddam et al., 2023). The remaining three studies were oriented toward theoretical analysis of

equity-efficiency trade-offs applicable across healthcare resource provisioning contexts, providing analytical foundations without domain restriction (Breugem & Van Wassenhove, 2022; Argyris et al., 2022; Gutjahr, 2026).

Publication years reflected a marked acceleration in equity-explicit optimization research following the COVID-19 pandemic. Only two studies predated the acute pandemic response period of 2021, and most of the included work was published between 2022 and 2025, with five studies appearing in 2026. This temporal clustering suggests that the COVID-19 pandemic functioned as a structural catalyst, forcing public health researchers and operations scientists to confront the practical urgency of formalizing equity criteria in allocation models rather than treating fairness as a secondary concern.

Table 1: Summary of Included Studies on Optimization Models for Equitable Public Health Resource Allocation (2021–2026)

(N = 29)

Author (Year)	Country / Setting	Public Health Domain	Optimization Model	Equity Metric & Operationalization	Key Finding
Bui et al., (2024)	USA (Arkansas)	Vaccine allocation	Multi-stage stochastic programming	Price of fairness; equitable regional distribution constraint embedded in MSP objective	Delaying ventilator redeployment increased expected deaths by ~285/month; price of fairness peaked during outbreak surges
Anderson et al., (2025)	USA (New York)	Critical care rationing	Queuing theory / integer programming	Explicit racial disparity hard constraint requiring minimum allocation to historically underserved racial groups	Racial equity constraint reduced access gap without significant increase in overall mortality
Cheong, (2026)	USA	Disability accessibility	Linear programming (LP)	Minimum disability coverage threshold embedded as LP constraint for disabled population subgroup	Disability equity constraints improved coverage with modest and bounded efficiency cost
Akbari-Moghaddam et al., (2023)	Canada	Convalescent plasma allocation	Data-driven mixed-integer programming (MIP)	Minimax unmet demand ratio across hospital hubs as equity objective	MIP equitably distributed scarce convalescent plasma across hospital hubs; reduced inter-hub supply-demand imbalance
Pérez et al., (2025)	USA	Trauma hospital network expansion	Stochastic programming (SP)	Rural and underserved community minimum coverage constraint embedded in SP structure	Rural equity constraints materially shifted optimal hospital siting decisions; underserved coverage improved substantially
Stafford et al., (2023)	USA (Oregon)	COVID-19 vaccine allocation	Compartmental model with optimization	Five explicit equity metrics (racial/ethnic mortality, infection, hospitalization disparities)	Equity-optimized allocations reduced racial disparities in COVID-19 outcomes; clear efficiency-equity

				embedded as co-objectives	trade-off at low coverage levels
Bowring et al., (2024)	USA	HIV resource allocation	Fairness-aware mathematical optimization	Demographic disparity reduction constraints across racial and socioeconomic groups	Fairness constraints identified resources needed beyond efficiency-only allocations; equity-constrained solutions reduced demographic access gaps
Sengul Orgut et al., (2023)	USA (Alabama)	Vaccine allocation (hesitancy-adjusted)	Mixed-integer linear programming (MILP)	Minimax travel time across counties as equity objective; geographic access equity embedded in MILP	Equity-adjusted model substantially differed from standard coverage-maximizing plans; access disparities reduced across rural counties
Thul & Powell, (2023)	USA (50 states)	Vaccine and test kit allocation	Stochastic optimization (multi-agent)	Equitable distribution priority for vulnerable populations embedded as allocation weighting in stochastic model	State coordination critical for equity outcomes; stochastic model reduced shortages while maintaining equitable distribution across states
Chen et al., (2025)	USA (Pennsylvania)	Opioid settlement allocation	Convex optimization	Dual formal fairness measures: proportional fairness and max-min fairness embedded as co-objectives	Framework reduced community-level disparities in opioid settlement fund distribution; both fairness objectives influenced optimal allocation
Bertsimas et al., (2022)	USA	COVID-19 vaccination facility siting	Data-driven integer programming (IP)	Minimum proportional coverage constraint for underserved ZIP codes embedded in IP facility location model	Data-driven siting substantially improved equitable facility access for underserved communities compared to naive geographic placement
Kim et al., (2025)	USA (New York City)	COVID-19 vaccine prioritization	Transmission model with optimization	Explicit Atkinson inequality aversion parameter embedded in objective function as equity-efficiency trade-off weight	Higher inequality aversion prioritized younger BIPOC groups; equity and efficiency objectives aligned at intermediate aversion levels
Hantel et al., (2022)	USA	Chemotherapy shortage (oncology)	Equity-oriented triage optimization	Minimum access threshold for curative-intent patients embedded as equity constraint in triage allocation model	Structured equity triage reduced arbitrary disparity in chemotherapy access; equity constraints prevented disproportionate exclusion of curative patients

Barth et al., (2024)	USA	Vaccine allocation with behavioral feedback	Dynamic programming (spatiotemporal)	Ex ante and ex post fairness constraints; freeze constraints preventing allocation reversal embedded in DP	Ex ante fairness produced more predictable and equitable allocation timelines; spatiotemporal equity constraints significantly altered optimal dynamic schedules
Manshadi et al., (2023)	USA (FEMA, national)	Emergency PPE allocation	Dynamic stochastic rationing model	Parity-preserving allocation (PPA) policy: formal fairness bounds on allocation ratios across states embedded in model	PPA fairness guarantee achievable at near-zero efficiency cost; formal guarantee substantially reduced inter-state allocation disparities
Abreu et al., (2025)	Portugal	Ambulance planning (EMS)	Mixed-integer linear programming (MILP)	Horizontal and vertical equity constraints both formally embedded in MILP structure	Dual-equity MILP substantially improved ambulance coverage equity; dynamic relocation with equity constraints outperformed static methods
Mohammadi et al., (2024)	France	Vaccine and quarantine planning	Mixed-integer nonlinear programming (MINLP)	Minimum coverage floor constraints for population age/risk classes embedded in MINLP	Equity constraints counter-intuitively increased total infections vs. efficiency-only model; fractional dosing mitigated the equity-efficiency trade-off
Mukherjee et al., (2025)	USA (Midwest)	Chronic disease (diabetes) care	Dynamic programming + ML hybrid	Sociodemographic equity embedded in DP prescriptions; race, SES, and SDOH as structural allocation parameters	Sociodemographically -informed DP improved outcomes for disadvantaged subgroups more than standard scheduling; equity-informed prescriptions reduced population-level risk differentials
Li et al., (2025)	USA (Pennsylvania)	COVID-19 vaccine spatial distribution	MILP with Lagrangian relaxation and Voronoi	Demographic equity constraints across race, age, and gender at census block level; deviation target ≤ 0.07 embedded in MILP	50% reduction in equity deviation; 28.15% increase in demand coverage; transportation cost reduced by 5.92% vs. baseline
Han et al., (2021)	United Kingdom	Hepatitis C treatment	Linear programming (LP)	Minimum budget allocation floor for marginalized groups (PWID, MSM) embedded as LP equity constraint	LP with equity constraint identified allocation treating 2,430 more patients and averting 78 liver

					deaths at equivalent cost
Erdoğan et al., (2024)	United Kingdom	COVID-19 vaccine allocation	Nonlinear mixed-integer programming (SIR-based)	Location inequity in mortality ratios as co-objective; minimize total mortality AND mortality ratio disparities simultaneously	Bi-objective framework revealed significant trade-off between mortality minimization and location equity; vaccine availability most significant parameter for both objectives
Basciftci et al., (2023)	USA	COVID-19 vaccine and test kit distribution	Stochastic programming (SP) and distributionally robust optimization (DRO)	Equity as co-objective in both SP and DRO; worst-case unmet demand prioritization enables equity-efficiency trade-off analysis	DRO preferred when worst-case equity prioritized; SP provides near-equitable plans under budget constraints with minimal efficiency compromise
Breugem & Van Wassenhove , (2022)	HIC (general)	Health resource delivery	Formal optimization with outcome constraints	Vertical equity via asymmetric outcome constraints specifying minimum utility fraction per subgroup; analytical bounds derived	Closed form bounds on price of vertical equity derived; equity constraints entail substantial but bounded efficiency costs in health delivery
Argyris et al., (2022)	HIC (general)	Healthcare resource provisioning	Multi-level mathematical optimization	Welfare dominance constraints embedding fairness axioms (efficiency, equity, inequality aversion) in model structure	Parameterized equity-efficiency trade-off surface derived; sensitivity to inequality aversion coefficient mapped across healthcare provisioning scenarios
Canellas et al., (2025)	USA (academic medical center)	Emergency department patient placement	MILP (predictive-prescriptive)	Race and gender equity constraints on wait time disparities formally embedded in MILP with convergence guarantees	MILP increased ED throughput and reduced average wait time; racial and gender wait time biases addressed without material efficiency loss
Cunningham et al., (2021)	USA	Post-disaster mental health	Simulation-optimization (LP coupled)	CDC Social Vulnerability Index (SVI) formally integrated as equity criterion driving resource assignment in optimization	SVI-informed framework improved equitable allocation of mental health resources to vulnerable post-disaster populations; reduced long-term mental health disparities
Gutjahr, (2023)	Austria	COVID-19 vaccine allocation	Optimization with generalized Gini index	Gini index embedded in objective function as equity penalty term combined with	APR allocation minimizes outcome inequity; outcome-equity view yields materially different

				utilitarian efficiency; applied to outcome equity (infection escape rates, not input fractions)	prioritization than input-equity approaches
Gutjahr, (2026)	HIC (theoretical)	Age-based health resource allocation	Optimization with Gini-based egalitarian social welfare function	Gini-index social welfare function embedding fair innings egalitarian equity across age strata; inequality aversion parameter embedded in objective	Priority for younger populations demonstrated under restricted conditions; egalitarian and prioritarian models yield different age-allocation prescriptions
Ma et al., (2023)	USA (Florida)	Preventive dental care (school-based)	Caseload reallocation optimization	Minimum coverage thresholds for uninsured and Medicaid-enrolled children embedded as equity constraints in caseload allocation model	Equity-constrained optimization improved dental care access for uninsured children; insurance-based access disparities reduced through constrained caseload reallocation

Note. MILP = mixed-integer linear programming; SP = stochastic programming; DP = dynamic programming; MIP = mixed-integer programming; MINLP = mixed-integer nonlinear programming; DRO = distributionally robust optimization; LP = linear programming; SVI = Social Vulnerability Index; PWID = people who inject drugs; MSM = men who have sex with men; BIPOC = Black, Indigenous, and People of Color; HIC = high-income country; EMS = emergency medical services; PPE = personal protective equipment.

3.3 Optimization Model Architectures

A review of all included studies showed a wide range of formal mathematical optimization architectures, indicating substantial methodological diversity in public health resource allocation research. Mixed integer linear programming was the most frequently used approach, appearing in eight studies as either a standalone method or part of a hybrid framework (Sengul Orgut et al., 2023; Abreu et al., 2025; Li et al., 2025; Canellas et al., 2025; Anderson et al., 2025; Bertsimas et al., 2022; Akbari-Moghaddam et al., 2023; Erdogan et al., 2024). Stochastic programming, including two-stage, multi-stage, and distributionally robust formulations, was used in seven studies and was commonly applied to settings involving uncertainty in demand forecasting and resource allocation (Bui et al., 2024; Pérez et al., 2025; Thul & Powell, 2023; Manshadi et al., 2023; Basciftci et al., 2023; Barth et al., 2024; Mohammadi et al., 2024). Linear programming appeared in three studies, mainly where equity constraints were deterministic or analytically tractable (Han et al., 2021; Cheong, 2026; Cunningham et al., 2021). Dynamic programming, including spatiotemporal variants and hybrid machine learning approaches, was used in three studies focused on time-dependent allocation decisions such as vaccine distribution and chronic disease encounter scheduling (Barth et al., 2024; Mukherjee et al., 2025; Manshadi et al., 2023). Non-linear programming formulations, including mixed integer nonlinear programming and SIR coupled models, were used in two studies that incorporated disease transmission dynamics directly into the optimization framework (Mohammadi et al., 2024; Erdogan et al., 2024).

Several studies used specialized architectures that embedded equity directly within the mathematical structure of the model. Generalized Gini index and egalitarian social welfare functions incorporated distributional fairness into the aggregation function rather than treating equity as an external constraint (Gutjahr, 2023, 2026). Predictive prescriptive frameworks also appeared in the corpus. In emergency department operations, a predictive prescriptive mixed integer linear programming model combined demand forecasting with constrained scheduling to address both efficiency and fairness (Canellas et al., 2025). In diabetes care optimization, dynamic programming was combined with machine learning to generate socio-demographically informed encounter prescriptions (Mukherjee et al., 2025).

Other studies addressed uncertainty and fairness through methodological variation. Comparative analyses of stochastic programming and distributionally robust optimization showed that different uncertainty representations produced different equity-efficiency trade-offs, with distributionally robust formulations generally offering stronger worst-case fairness guarantees and stochastic approaches yielding more practical intermediate solutions (Basciftci et al., 2023). Theoretical work also showed that parity-preserving allocation constraints can be implemented with provably bounded efficiency loss, providing formal guarantees alongside simulation-based evidence (Manshadi et al., 2023). Simulation optimization was another recurring approach. In post-disaster mental health allocation, state transition simulation was

coupled with linear programming to allocate resources according to population vulnerability measured by the CDC Social Vulnerability Index (Cunningham et al., 2021). Additional theoretical studies provided analytical characterizations of equity-efficiency trade-off surfaces and formal foundations for subsequent applied work (Argyris et al., 2022; Breugem and Van Wassenhove, 2022).

3.4 Operationalization of Equity Metrics

Equity operationalization was the most heterogeneous aspect of the corpus. Across the 29 studies, three dominant approaches appeared: embedding equity as a structural constraint, incorporating equity as a co-objective alongside efficiency, and parameterizing equity directly within the objective function. These approaches reflected different definitions of fairness, ranging from fixed allocation requirements to continuously adjustable social preferences.

The most common strategy across the corpus was to embed equity as a structural constraint. Sixteen studies used this approach, though the specific mechanisms varied considerably by domain. Sengul Orgut et al. (2023) operationalized geographic access equity through minimax travel time constraints, capping the worst-case travel distance for patients across Alabama counties. In facility siting, Bertsimas et al. (2022) imposed minimum proportional coverage requirements for underserved ZIP codes so that marginalized communities were not bypassed in optimal placement decisions. Treatment allocation models took a different route: Han et al. (2021) established minimum budget floors for people who inject drugs and men who have sex with men in hepatitis C treatment planning, demonstrating that such constraints could expand treatment reach without additional expenditure. Pérez et al. (2025) embedded minimum coverage thresholds for rural communities in trauma hospital network planning, while Hantel et al. (2022) set minimum access guarantees for curative-intent oncology patients during chemotherapy shortages. Some formulations went further by embedding both horizontal equities, meaning equal treatment for equal need, and vertical equity, meaning proportionate treatment for unequal need, simultaneously within a single MILP framework (Abreu et al., 2025). Li et al. (2025) applied demographic fairness constraints across race, age, and gender at the census block level, achieving substantial reductions in equity deviation while improving overall service coverage. Across all sixteen studies, equity was non-negotiable: it shaped the feasible solution space rather than serving as a secondary consideration after efficiency was maximized (Bui et al., 2024; Manshadi et al., 2023; Bowring et al., 2024; Anderson et al., 2025; Cheong, 2026; Ma et al., 2023; Cunningham et al., 2021; Akbari-Moghaddam et al., 2023; Mohammadi et al., 2024).

A second major strategy treated equity as a co-objective to be optimized alongside, rather than constrained against, efficiency. Rather than imposing fixed fairness floors, eleven studies using this approach characterized the full Pareto frontier so that decision-makers could see precisely what efficiency is traded away at each level of equity improvement. In pandemic vaccine allocation, Stafford et al. (2023) optimized multiple racial and ethnic disparity measures concurrently with mortality reduction objectives, finding that the tension between them largely dissolved at higher vaccine coverage levels. Erdogan et al. (2024) minimized both total mortality and location-level inequity in mortality ratios simultaneously, finding that vaccine availability was the single most influential parameter on both dimensions. Basciftci et al. (2023) ran stochastic programming and distributionally robust optimization in parallel, demonstrating that the choice of uncertainty model itself reshapes the equity-efficiency profile, with the robust formulation offering stronger worst-case fairness guarantees. Beyond pandemic settings, Chen et al. (2025) embedded dual proportional and max-min fairness objectives in opioid settlement fund allocation, while Mukherjee et al. (2025) incorporated sociodemographic equity as a continuous optimization target in diabetes care scheduling. Theoretical contributions by Breugem and Van Wassenhove (2022) and Argyris et al. (2022) provided formal characterizations of the equity-efficiency frontier. The remaining studies in this group (Kim et al., 2025; Thul & Powell, 2023; Barth et al., 2024; Pérez et al., 2025) similarly surfaced equity-efficiency trade-offs as explicit choices for decision-makers rather than embedding them inside technical parameters.

A smaller but methodologically distinct group of studies embedded equity directly within the objective function. These approaches treated fairness as a continuously adjustable preference rather than a binary requirement. Inequality aversion parameters allowed decision makers to vary the relative weight placed on fairness and efficiency, producing different allocation recommendations as preferences changed (Kim et al., 2025). Generalized Gini indices and egalitarian social welfare functions similarly embedded distributive justice directly into the objective function, shifting attention from equitable resource inputs to equitable health outcomes (Gutjahr, 2023, 2026). Welfare dominance constraints and inequality aversion frameworks provided formal mathematical structures for evaluating how allocations changed under alternative fairness principles and social welfare assumptions (Argyris et al., 2022).

3.5 Equity Efficiency Trade-offs and Key Outcomes

Across the corpus, the relationship between equity and efficiency was consistent but varied by domain, model structure, and equity definition. Formal incorporation of equity generally improved distributive fairness, while the associated efficiency costs ranged from minimal to substantial. Several studies showed that equity and efficiency were not always competing objectives and could under some conditions be mutually reinforcing.

The most pronounced trade-offs appeared in pandemic and vaccine allocation settings, particularly under severe scarcity. Multi-objective vaccine allocation models showed that optimizing for equity at low coverage levels could reduce deaths averted, while the trade-off diminished as vaccine availability increased. At higher coverage levels, equity and efficiency objectives were often simultaneously attainable (Stafford et al., 2023). Other studies found that equity constraints could increase total infections relative to efficiency-maximizing baselines, although complementary policy tools such as fractional dosing reduced these costs (Mohammadi et al., 2024). These findings suggest that the magnitude of the trade-off depended not only on equity requirements but also on the policy environment in which they were implemented.

In chronic disease management and other non-pandemic settings, the equity-efficiency relationship was generally more favorable than in acute pandemic contexts, and in several cases the two goals reinforced rather than opposed each other. Han et al. (2021) found that embedding a minimum allocation floor for marginalized groups in a hepatitis C treatment LP model in the United Kingdom produced a solution that treated 2,430 more patients and averted 78 liver-related deaths compared to the unconstrained baseline, all at equivalent cost. Rather than imposing an efficiency penalty, the equity constraint corrected a structural distortion in the original allocation. A similar pattern emerged in preventive dental care: Ma et al. (2023) showed that equity-constrained reallocation of school-based dental program caseloads in Florida improved access for uninsured children without reducing aggregate service delivery. In emergency department operations, Canellas et al. (2025) demonstrated that embedding race and gender equity constraints in a predictive-prescriptive MILP for patient placement simultaneously improved throughput and reduced demographic wait time disparities, with no material operational penalty. These findings point to a consistent pattern: when allocation systems have accumulated inefficiency through structural inequity or historical inertia, formally embedding equity does not subtract from performance but instead redirects resources more productively.

Evidence from emergency care and acute service delivery further supported the compatibility of fairness and performance in some settings. Equity constraints in emergency department patient placement improved operational throughput while reducing race and gender disparities in waiting times (Canellas et al., 2025). Dynamic ambulance relocation models incorporating horizontal and vertical equity requirements outperformed traditional deployment approaches on coverage and fairness measures (Abreu et al., 2025). Racial equity constraints in critical care rationing reduced disparities in access without statistically significant increases in mortality (Anderson et al., 2025). Together, these studies suggest that advanced optimization frameworks can incorporate equity requirements with limited operational penalty.

Theoretical studies provided additional context for these findings. Analytical investigations established formal bounds on the price of equity and showed that efficiency losses depend on subgroup utility distributions, outcome asymmetries, and the specific form of the equity constraint used (Breugem and Van Wassenhove, 2022). Other work showed that parity preserving allocation policies can be implemented with near zero efficiency loss in dynamic rationing environments (Manshadi et al., 2023). Together, these theoretical contributions indicate that the efficiency costs of equity are not fixed properties of allocation problems but depend on model structure, fairness operationalization, and complementary policy mechanisms.

4 DISCUSSION

This systematic review synthesized 29 peer-reviewed studies published between 2021 and 2026 that formally embedded equity or fairness metrics within mathematical optimization models applied to public health resource allocation. The evidence indicates a rapidly developing field, shaped in large part by the COVID-19 pandemic and characterized by substantial methodological diversity in both optimization structure and equity operationalization. Three principal findings emerge. First, equity can be formally embedded across a wide range of mathematical programming paradigms. Second, the efficiency costs of doing so are often modest, bounded, or absent, especially when allocation systems already reflect structural inefficiencies rooted in historical inequities. Third, the equity efficiency relationship is not fixed, but depends on model architecture, the form of equity operationalization, and the policy instruments available to decision makers.

4.1 Feasibility and Architecture of Equity Explicit Optimization

The breadth of optimization architectures in this corpus is itself an important finding: equity can be embedded across virtually every major mathematical programming tradition. MILP frameworks handled equity well in geographically dispersed problems where binary location decisions needed to respect coverage thresholds for underserved populations (Sengul Orgut et al., 2023; Abreu et al., 2025; Li et al., 2025). Stochastic programming accommodated equity under uncertainty, embedding fairness constraints in settings where demand and supply were probabilistic rather than fixed (Bui et al., 2024; Thul & Powell, 2023; Basciftci et al., 2023). Dynamic programming captured equity over time, particularly in vaccine campaigns where fairness needed to hold across sequential decision points (Barth et al., 2024). Nonlinear programming supported equity when disease transmission dynamics were embedded directly in the

optimization structure (Erdogan et al., 2024; Mohammadi et al., 2024). Convex and hybrid machine learning-optimization architectures successfully embedded dual fairness objectives and sociodemographic equity parameters respectively (Chen et al., 2025; Mukherjee et al., 2025). The practical implication is that public health decision-makers are not constrained to a single modeling paradigm and can select the architecture most suited to their data, computational resources, and policy context while still formally incorporating equity.

The COVID-19 pandemic appears to have accelerated this methodological development. The disproportionate burden of COVID-19 on racial and ethnic minority populations in the United States, including higher rates of infection, hospitalization, and mortality among Black, Indigenous, and Hispanic communities (Tai et al., 2022), created both ethical urgency and practical pressure to move beyond efficiency-only allocation models. Standard allocation rules that prioritize those most likely to benefit can reinforce pre-existing structural inequities when advantage is already shaped by social determinants of health (Schmidt et al., 2020). In that sense, the studies in this corpus represent an operational research response to a long-standing public health problem, translating equity into formal constraints or objectives rather than leaving it to post hoc interpretation.

A particularly important methodological contribution is the use of equity not only as an added constraint, but as a feature of the objective function itself. Gutjahr (2023, 2026) used a generalized Gini index and egalitarian social welfare objectives to assess equity across outcome distributions rather than input allocations. This distinction matters because equal resource shares do not necessarily produce equal outcomes when baseline vulnerability, access barriers, and biological risk differ across populations (Breugem and Van Wassenhove, 2022). Outcome-based equity also aligns more closely with public health definitions that emphasize the fair distribution of health outcomes and the removal of barriers to attaining optimal health (Centers for Disease Control and Prevention [CDC], 2024).

4.2 Equity Operationalization

The reviewed studies show three main ways of operationalizing equity, each reflecting a different conception of fairness and a different role for decision-makers in the allocation process.

The first approach treats equity as a structural constraint. Sixteen studies used minimum coverage thresholds, disparity limits, minimax access requirements, or allocation floors for vulnerable populations. In this framework, equity functions as a non-negotiable condition that feasible solutions must satisfy. This approach is especially policy relevant because it can be translated into coverage guarantees, procurement rules, and distribution agreements. It also has the potential to identify Pareto improvements in systems where historical allocation patterns have been shaped by structural bias rather than genuine efficiency considerations (Akbari-Moghaddam et al., 2023; Cheong, 2026; Han et al., 2021; Sengul Orgut et al., 2023; World Health Organization, 2025)

The second approach treats equity as a co-objective alongside efficiency. Eleven studies used multi-objective or bi-criteria formulations to characterize the Pareto frontier between competing goals. This makes the trade-off visible rather than hiding it inside a single objective function. Such models are useful when the appropriate balance between fairness and efficiency is politically contested or depends on changing conditions. They also show that expanding supply can reduce apparent trade-offs, as seen in studies where equity and efficiency converged at higher coverage levels (Bui et al., 2024; Larsson, 2024; Stafford et al., 2023; Thul & Powell, 2023). The third approach embeds equity directly in the objective function through inequality aversion parameters or welfare-based formulations. These models make fairness a continuous and adjustable preference rather than a binary rule. Kim et al. (2025) showed that changing the equity parameter meaningfully altered allocation recommendations, including a shift toward younger, higher transmission BIPOC groups at higher aversion levels. This has direct implications for transparency and accountability because the choice of equity weight should be explicit and subject to deliberation rather than determined solely by technical analysts (Argyris et al., 2022).

4.3 Rethinking the Equity Efficiency Trade-Off

A central assumption in public health allocation is that equity and efficiency are inherently competing goals. The evidence in this corpus complicates that assumption. Although trade-offs are real in conditions of severe scarcity, especially in pandemic vaccine distribution at low coverage levels (Stafford et al., 2023; Mohammadi et al., 2024), most studies found that the efficiency costs of equity were modest, bounded, or absent. This is consistent with theoretical work showing that the price of vertical equity depends on the structure of the allocation problem rather than being an inevitable feature of equity-constrained optimization (Breugem and Van Wassenhove, 2022).

This pattern is especially important in settings where historical allocation systems are already structurally inefficient. When inequity has accumulated through structural racism, geographic disadvantage, or institutional inertia, the unconstrained efficiency maximizing solution is not necessarily a true Pareto optimum. In such cases, equity constraints may not impose losses so much as correct distortions. This is reflected in the dental care context studied by Ma et al. (2023), where equity-constrained reallocation improved access for uninsured children without reducing aggregate

service delivery, and in the emergency department context of Canellas et al. (2025), where racial and gender equity constraints improved throughput while reducing wait time disparities.

The finding by Manshadi et al. (2023) that parity-preserving policies can be implemented with near-zero efficiency loss is especially important. It directly challenges the claim that fairness requirements are incompatible with effective emergency response. In public health emergency preparedness, where allocation decisions during the COVID-19 pandemic were closely scrutinized for inequity, formal optimization models that guarantee fairer distribution without major efficiency loss provide a strong technical counterpoint to the view that equity is a luxury.

4.4 Translational Barriers in U.S. Public Health Infrastructure

Most studies in the corpus were conducted in the United States, reflecting both the need for equity-explicit allocation tools and the structural barriers to implementation in a fragmented public health system (McClellan et al., 2025). Several studies improved translational relevance by using operationally familiar data sources, such as the CDC Social Vulnerability Index or ZIP code-level information already used in public health practice (Cunningham et al., 2021; Bertsimas et al., 2022). These design choices reduce the gap between model output and policy action.

Even so, a major implementation challenge remains. Local public health agencies often do not have the technical expertise needed to run or adapt optimization models. Future deployment efforts should therefore focus on open-source decision support tools with graphical interfaces that allow practitioners to adjust equity thresholds without modifying source code. Without such translation tools, highly sophisticated models are likely to remain confined to research settings rather than being used in practice.

4.5 Methodological Considerations and Limitations

This review intentionally focused on studies that formally embedded equity metrics, so it does not capture the broader literature on equity in public health resource allocation that uses qualitative or policy-based methods. The heterogeneity of equity metrics, optimization methods, and public health settings also prevented quantitative meta-analysis. For that reason, the review relies on structured narrative synthesis in line with SWiM guidelines (Campbell et al., 2020). Most included studies evaluated models through simulation or retrospective analysis rather than prospective implementation. As a result, demonstrated equity gains may not fully translate into routine practice, where implementation fidelity, stakeholder acceptance, and real-time data availability matter greatly (Husain et al., 2025). The focus on the United States and other high-income settings also limits generalizability to lower resource contexts, where different data systems and institutional constraints may require substantial model adaptation (World Health Organization, 2025).

4.6 Future Research Directions

Future research should focus on three priorities. First, machine learning and optimization should be integrated more carefully, with attention to algorithmic bias at both the prediction and prescription stages. Second, dynamic models should extend the time horizon of equity analysis so that cumulative and path-dependent effects are captured rather than assessed at a single point in time. Third, implementation science should be built into model development from the start so that stakeholder engagement, data readiness, and regulatory compatibility are addressed alongside technical performance.

5 CONCLUSION

This systematic review shows that equity can be formally embedded within public health resource allocation models across a wide range of optimization architectures, and that doing so often improves distributive fairness without imposing large efficiency losses. The evidence suggests that equity and efficiency should not be treated as fixed opposites, because their relationship depends on model design, the operational definition of fairness, and the policy environment in which the model is applied. In many settings, especially where historical allocation systems are already distorted by structural inequities, equity-constrained optimization may improve both fairness and performance. These findings support a shift away from efficiency-only allocation frameworks toward decision tools that make fairness explicit, transparent, and operationally actionable. Future work should focus on prospective implementation, stronger integration of implementation science, and user-friendly decision support tools that allow public health agencies to apply equity-explicit models in real time.

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