Feasibility of Low-Cost Diagnostic Microscopy: A Systematic Review for Field-Based Applications

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Abstract

Microscopy remains a cornerstone of medical diagnostics, yet its accessibility in resource-limited and field-based settings is constrained by high costs, specialized training requirements, and infrastructural demands. This study presents a cross-cutting systematic review of field-deployable microscopy approaches relevant to diagnosis and clinical decision support across domains encompassing hematology, cytology, dermatology, microbiology, and ophthalmology. We cross-reference over 90 diagnostic tasks with the spatial and optical requirements of field-deployable imaging platforms, emphasizing compatibility with smartphone-based and open-source microscopy systems. A structured feasibility matrix is introduced, mapping each diagnostic application to resolution, field of view, and depth of field parameters derived from clinical gold standards. We further assess the usability of these tasks by non-experts, accounting for sample preparation complexity, interpretive burden, and risk of misclassification. Building on this framework, we introduce a curated set of device specifications designed to meet the minimal viable criteria for over 30 high-impact diagnostic tasks using open hardware. The resulting taxonomy offers an evidence-based scaffold for prioritizing diagnostic applications that are both technically feasible and socially scalable. This convergence of optical engineering, disease burden mapping, and usability assessment advances the translation of low-cost imaging into global health, agricultural monitoring, and decentralized laboratory settings.

Keywords: Microscopy, Open-source hardware, Diagnostic usability, Resource-limited diagnostics, Global health, Imaging optics

1 Introduction

Microscopy is a cornerstone of diagnostic medicine, enabling direct visualization of cellular, microbial, and tissue-level characteristics for identifying a wide range of pathological conditions. From hematological assessments to infectious disease detection, microscopy remains indispensable in clinical workflows and research laboratories alike. Despite its foundational role, conventional microscopy is often inaccessible in low-resource, rural, and field-based settings. Several barriers hinder their widespread deployment, including high costs, the need for continuous electrical power and stable environments, and the requirement for skilled technicians to prepare and interpret samples. These constraints are particularly pronounced in global health contexts, where healthcare infrastructure may be limited and disease burden disproportionately high. As a result, critical diagnostic services are frequently delayed or unavailable, reinforcing systemic inequities in healthcare delivery. In response to these challenges, a new class of open-source and portable imaging systems has emerged, leveraging advances in miniaturized optics, smartphone integration, and low-cost digital fabrication.

To contextualize the complexity and structure of diagnostic workflows reviewed in this study, we introduce a layered abbreviation legend aligned with the Sankey-style diagram of clinical operations (Table 1). This table organizes the relevant sample types, processing steps, imaging modalities, and diagnostic endpoints from left to right, mirroring the logical sequence in a typical field-deployable microscopy pipeline. By mapping each step in the pathway to its abbreviated form, the table supports rapid cross-referencing between the visual diagram (Figure 1) and the technical narrative. This structured format also highlights the standardized and overlapping operations across multiple diagnostic tasks, reinforcing the feasibility of modular, open-source microscopy solutions for a broad spectrum of use cases.

Multiple low-cost, smartphone-compatible, and open-source microscopy platforms have been developed to address the specific constraints of field-deployable diagnostic applications. The Foldscope is a paper-based microscope utilizing a ball lens and LED illumination, capable of achieving submicron spatial resolution. Its construction from low-cost materials enables mass production and disposable use, addressing affordability, portability, and biosafety [1]. The OpenFlexure microscope employs 3D-printed flexure mechanisms to provide precise XYZ translation and stabilization of optical components. The design supports smartphone integration and modular component replacement, aligning with attributes such as open-source compatibility, optical performance, and robustness [2]. The CellScope platform integrates custom optics, micro-LED arrays, and smartphone imaging to facilitate automated scanning of prepared slides. It has demonstrated efficacy in detecting tuberculosis bacilli and parasitic infections, and addresses attributes including diagnostic accuracy, data handling, and ease of use through smartphone-based automation [?]. The μ-Phone system incorporates molded lenses and a mechanically stabilized sample stage with digital acquisition via a smartphone. It supports diagnostic tasks such as blood smear analysis and microbial culture inspection, with a reported resolution of approximately 1.5 μm, addressing optical performance, power independence, and field readiness [3]. The GravelScope implements a lens-free, holography-based design using LED back-illumination and algorithmic reconstruction, allowing large field-of-view imaging without reliance on

Table 1 Layered Abbreviation Legend Aligned with Diagnostic Flow

	Sample Type		Collection Stage		Processing Step		Preparation
BLD	Blood	REC	Patient Recruitment	TRN	Transport	WTM	Wet Mount
URN	Urine	CNS	Consent	SCR	Initial Screening	KOH	KOH Mount
STL	Stool	COL	Sample Collection	LBL	Labeling	GRM	Gram Stain
SPT	Sputum			CNF	Centrifugation	PAP	PAP Stain
SKN	Skin			FIX	Fixation	ZNH	Ziehl-Neelsen
CVX	Cervix			SMR	Smearing	WRG	Wright-Giemsa
FNA	Fine Needle Aspiration			CCT	Concentration	HNE	H&E Stain
EFF	Effusion						
CRN	Cornea						
SEM	Semen						

	Imaging Step		Diagnosis / Clinical Impact		Diagnosis / Clinical Impact		Diagnosis / Clinical Impact
IMG	Digital Capture	MAL	Malaria	KID	Kidney Pathology	CRU	Corneal Ulcer
		ANM	Anemia	PAR	Parasitic Infection	THY	Thyroid Nodule
		UTI	Urinary Tract Infection	GIB	GI Bleeding	LYM	Lymphoma
		TB	Tuberculosis	SPM	Sperm Motility	EDU	Education/Training
		FNG	Fungal Infection				
		HPV	HPV Lesion				
		LEU	Leukemia				
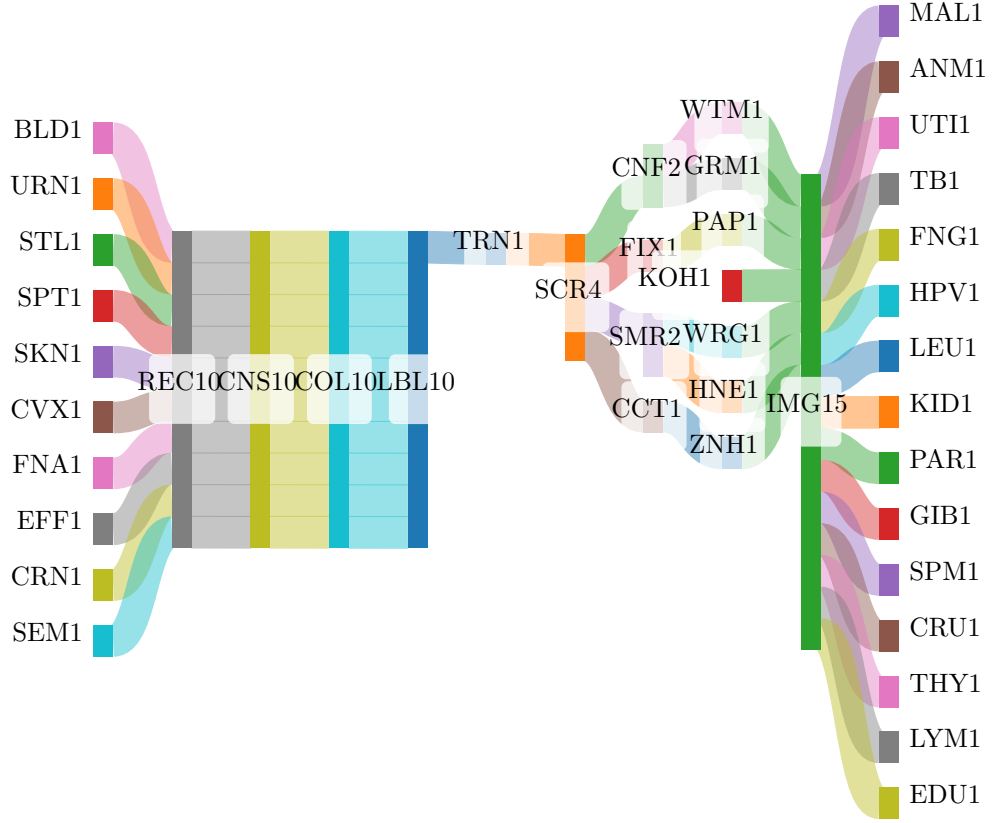
Fig. 1 Clinical Workflows

precision optics. This system reduces power consumption and mechanical complexity, thereby addressing portability, power independence, and sample throughput [4]. Collectively, these systems represent a range of hardware strategies aimed at satisfying the minimal viable criteria for diagnostic imaging under constrained environmental and infrastructural conditions.

These systems offer viable alternatives to conventional benchtop microscopes for low-cost, field-deployable diagnostics. However, despite the proliferation of such technologies, there remains a lack of clear guidance for engineers, clinicians, and potential funders or policymakers regarding their comparative suitability for deployment. Critical aspects—including clinical utility for specific diagnostic tasks, design economy

characterized by size, weight, power consumption, and cost (SWAP-C), and usability factors such as sample preparation complexity and the cognitive and interpretive burden on operators—are often insufficiently characterized and rarely evaluated in a cross-sectional or standardized manner. In this work, we seek to systematically assess modern low-cost field deployable microscopy systems for clinical decision support. This review introduces a structured cross-sectional analysis including clinical impact, SWAP-C considerations, and usability grounded in non-expert workflows. These attributes are listed in **??**.

Table 2 Hierarchical Classification of Attributes for Field-Deployable Diagnostic Tools

Attribute	Description
Clinical Impact	
Diagnostic Accuracy	Sensitivity and specificity compared to clinical gold standards.
Optical Performance	Includes spatial resolution, field of view, and depth of field necessary to visualize relevant targets.
Turnaround Time	Time from sample acquisition to diagnostic output.
SWAP-C Considerations	
Affordability	Includes manufacturing cost, cost per test, and maintenance. Influences scalability in low-resource settings.
Portability	Compactness, weight, and ease of transport. Includes ability to function off-grid or with minimal infrastructure.
Robustness	Durability under adverse environmental conditions (temperature, humidity, dust).
Power Independence	Ability to operate using battery power, solar energy, or manual components without reliance on mains electricity.
Open Compatibility	Availability of design files, documentation, and modifiability for local adaptation.
Usability	
Ease of Use	Level of training required; clarity of operation steps; user interface simplicity, particularly for non-expert users.
Sample Preparation	Time, skill, and materials required to prepare specimens for observation.
Data Handling	Ability to store, transmit, or analyze data digitally (e.g., via smartphone or cloud integration).
Biosafety	Risk of contamination or infection during use; design features for safe disposal or sterilization.

These attributes are essential enablers of field diagnostics, mobile clinics, and decentralized laboratory networks where conventional infrastructures are impractical or unavailable. However, the suitability of these tools for specific diagnostic applications remains largely uncharacterized. While many of these systems are capable of achieving impressive spatial resolution under ideal conditions, the real-world feasibility of deploying them across diverse diagnostic contexts depends on a multidimensional interplay of factors. These include not only the technical specifications of the imaging system—such as spatial resolution, field of view, and depth of field—but also the complexity of sample preparation, the cognitive and interpretive burden placed on the

operator, and the potential risk of diagnostic misclassification. To systematically assess the viability of such deployments, this review introduces a structured cross-sectional analysis that links each diagnostic task to a minimal optical requirement profile and overlays it with a usability framework grounded in non-expert workflows. By examining both the physical capabilities of emerging microscopy tools and the human factors that govern their effective use, we aim to identify high-leverage applications where open hardware platforms can achieve diagnostic parity with traditional systems while expanding access to underserved populations.

This review systematically evaluates the feasibility of applying low-cost microscopy systems to real-world diagnostic tasks across a range of medical and educational domains. We compile and cross-reference over 90 disease-relevant diagnostic tasks with corresponding optical performance criteria—resolution, field of view, and depth of field—and assess their usability by non-expert operators. These tasks are organized into a structured feasibility matrix informed by three primary attribute areas: clinical impact, SWAP-C (size, weight, power, and cost) considerations, and usability. By mapping diagnostic need to engineering constraints and user accessibility, this review provides an evidence-based scaffold for prioritizing diagnostic applications that are technically feasible, operationally usable, and globally scalable.

2 Methods

2.1 Review Design and Rationale

This review was designed to systematically evaluate the feasibility of low-cost, field-deployable microscopy platforms in performing clinically relevant diagnostic tasks. Specifically, we sought to cross-reference clinical utility in over 90 diagnostic tasks with the technical capabilities and usability profiles of low-cost microscopy platforms. Recognizing the diversity of emerging microscopy platforms, our goal was to construct a structured framework that allows comparison across three critical dimensions: clinical impact, SWAP-C (size, weight, power, and cost) considerations, and usability by non-expert operators. The review integrates literature from biomedical diagnostics, global health, and low-cost engineering to bridge the gap between real-world diagnostic needs and the engineering specifications of open-access hardware platforms. In doing so, it aims to inform decision-making by developers, clinicians, and funders seeking scalable, evidence-based tools for decentralized diagnostic settings.

2.2 Database Selection and Search Strategy

To capture the interdisciplinary landscape of low-cost, field-deployable microscopy, we conducted a structured literature search across three major information classes: (1) clinical diagnostic tasks, (2) optical and hardware system design, and (3) usability and implementation in low-resource settings. Each class was targeted using distinct search term clusters and source databases to ensure comprehensive coverage.

The search spanned four primary indexed databases: PubMed (clinical and biomedical diagnostics), Scopus (multidisciplinary peer-reviewed literature), Web of Science

(citation-linked discovery across science and engineering), and IEEE Xplore (engineering, optics, and device design). Together, these databases encompass clinical validation studies, hardware engineering publications, and translational applications of open-source and mobile diagnostics. Searches were conducted iteratively and finalized in January 2025.

1. Clinical Diagnostic Tasks. Searches targeting domain-specific diagnostic procedures were designed to identify microscopy-reliant clinical workflows across hematology, cytology, dermatology, microbiology, parasitology, ophthalmology, and infectious disease. These terms were combined with diagnostic task keywords to retrieve application-specific references:

> (("malaria" OR "tuberculosis" OR "trypanosomiasis" OR "Gram stain" OR "blood smear" OR "skin scraping") AND ("microscopy" OR "slide-based" OR "brightfield imaging"))

2. Imaging System Design and Optical Performance. To identify studies reporting system architecture, imaging modalities, and SWAP-C metrics, we used engineering-focused queries targeting both academic and maker-community platforms:

> (("low-cost microscope" OR "DIY microscope" OR "smartphone microscope" OR "portable microscope") AND ("resolution" OR "optical design" OR "3D-printed" OR "open-source hardware"))

IEEE Xplore and Web of Science were prioritized for hardware-specific search yields.

3. Usability and Field Deployment. To extract documentation related to operator burden, training requirements, or deployment in resource-limited contexts, we employed usability-centered search strings:

> (("field-deployable diagnostics" OR "point-of-care microscopy") AND ("sample preparation" OR "non-expert use" OR "usability" OR "operator training"))

Supplemental searches were performed in Scopus and PubMed to identify studies involving field trials and educational adaptations.

4. Grey Literature and Open Hardware Documentation. To incorporate community-driven innovation not represented in formal publishing venues, we manually screened preprint servers (bioRxiv, arXiv), open hardware directories (OSHWA, Public Lab, Hackaday), and project repositories (GitHub). Selection criteria included the availability of reproducible designs, device-level performance benchmarks, and reports of real-world use.

5. Citation Chaining. Backward and forward citation tracking was performed on foundational review papers and seminal articles on open-source microscopy platforms (e.g., Foldscope, OpenFlexure, CellScope). This process yielded additional studies not directly captured by keyword queries.

All search strings were adapted as needed to meet the syntax requirements of individual databases. No language restrictions were applied, though the majority of sources retrieved were in English.

2.3 Inclusion and Exclusion Criteria

Articles were eligible for inclusion if they: (i) described a diagnostic task involving visual interpretation of microscopy data; (ii) reported or allowed inference of optical

requirements (spatial resolution, field of view, depth of field); (iii) referenced a gold standard or benchmark diagnostic method; and (iv) presented a hardware platform or methodology relevant to decentralized, low-cost, or educational use. Studies involving human, veterinary, or plant diagnostics were considered.

Articles were excluded if they: (i) focused solely on algorithmic post-processing without addressing image acquisition; (ii) described exclusively high-end laboratory systems without consideration of portable alternatives; or (iii) lacked sufficient methodological detail to evaluate imaging parameters or usability.

2.4 Study Screening and Selection Process

All identified records were imported into Zotero for deduplication. Two reviewers independently screened titles and abstracts for relevance. Full-text review was performed for all retained articles using predefined criteria. Discrepancies were resolved through consensus discussion. A PRISMA 2020 flow diagram (Figure ??) summarizes the selection process.

2.5 Data Extraction and Feasibility Matrix Construction

Data were extracted using a custom-designed form in Airtable and cross-verified. Extracted variables included the clinical domain, specific diagnostic task, target analyte or structure, microscopy modality, spatial resolution (in m), field of view (in mm^2), depth of field (in m), device class (smartphone-based, open-source, proprietary portable), and reported gold-standard comparison (sensitivity, specificity, accuracy). Where not explicitly stated, imaging parameters were inferred based on diagnostic guidelines, comparable tasks, or validated device specifications.

These features were compiled into a structured feasibility matrix indexed by diagnostic task. The matrix included entries for: (1) minimum resolution threshold for task fidelity; (2) required field of view and DOF; (3) compatibility with smartphone imaging (Y/N); (4) compatibility with open-source hardware platforms; and (5) evidence of diagnostic accuracy.

2.6 Usability Evaluation

Each diagnostic task was evaluated using a structured usability framework comprising three axes: sample preparation complexity, interpretive burden, and misclassification risk. Preparation complexity was scored based on number of steps, need for reagents, and physical dexterity. Interpretive burden was judged on training time and cognitive load required for decision-making. Misclassification risk captured potential clinical consequences of false positives or negatives.

Each dimension was scored on an ordinal 3-point scale (1: low; 3: high). A composite deployability index was derived for each task and used to rank relative field-readiness under non-expert use.

2.7 Specification Matching and Synthesis

A set of candidate device configurations was modeled to match the optical demands of high-impact diagnostic tasks. These configurations were derived from prior literature on open-source microscopy, as well as specifications of documented low-cost systems. The synthesis process involved mapping each task to a set of minimum viable optical requirements and identifying compatible device architectures that met or exceeded those specifications. Preference was given to designs using plastic lenses, LED lighting, 3D-printed frames, and smartphone cameras with digital zoom and autofocus capabilities.

A final taxonomy was generated linking clinical task, optical feasibility, usability, and device compatibility. Results were synthesized narratively and in tabular format to guide future implementation efforts. No formal meta-analysis was performed due to heterogeneity in study designs, reporting standards, and measurement units.

3 Results

4 Discussion

5 Conclusion

Supplementary Information.   Supplementary tables and matrices available upon request or online.

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6 Declarations

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- **Materials availability:** ...
- **Code availability:** Not applicable.
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