RESEARCH PAPER

Comparative Study Of Novel Lensless Microscope With Marketed Trinocular Digital Microscope

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ABSTRACT
This study presents a comparative evaluation of a novel lensless microscope with a conventional marketed trinocular digital microscope (Olympus MX21i/CX21i series) for pharmaceutical and biological imaging applications. The proposed lensless system employs a nano–optical fiber–based illumination architecture coupled with a CMOS sensor and computational image reconstruction algorithms, eliminating the need for conventional optical lenses. The system integrates hardware and a Python-based software platform for image acquisition, enhancement, analysis, and report generation. A comprehensive comparison was performed using various pharmaceutical samples, including drug powders, emulsions, suspensions, liposomes, microencapsulated granules, polymeric microparticles, microspheres, and crystalline drug forms. Performance parameters such as image quality, resolution, field of view, portability, usability, and analytical reliability were evaluated. The lensless microscope demonstrated comparable performance to the marketed trinocular microscope in terms of qualitative image clarity and particle characterization, with an achieved spatial resolution of approximately 1.4 µm and improved edge-spread resolution of ~0.8 µm. The lensless system exhibited distinct advantages, including compact size, low cost, minimal optical alignment requirements, large field of view, and suitability for point-of-care and field-based applications. Software validation confirmed robust functionality, usability, and compatibility, enabling reliable image acquisition, processing, and reporting. The results indicate that the developed lensless microscope provides a viable and efficient alternative to conventional optical microscopes for pharmaceutical analysis and biomedical applications. Its portability, scalability, and cost-effectiveness make it particularly suitable for resource-limited environments, rapid diagnostics, and on-site analytical workflows.

Keywords: Lensless microscopy, CMOS sensor, Digital microscopy, Pharmaceutical analysis, Image processing, Computational imaging.
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1. Introduction

In the last few decades, significant breakthroughs in microscopy have been achieved, improving the spatio-temporal performance of various modalities such as optical microscopy, fluorescence microscopy, Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), and more. These advancements, largely fueled by the increasing availability of low-cost megapixel detectors and enhanced computing speeds since the 2000s, have paved the way for the emergence of digital lensless imaging— a technique that offers substantial advantages in biological and physics-based applications. [1]

Lensless microscopy, which avoids the use of traditional imaging optics, overcomes the limitations posed by optical aberrations and other mechanical constraints that typically degrade image quality in conventional systems. The simplicity of this approach, where a coherent light source illuminates a sample and the diffraction pattern is captured by a CCD or CMOS sensor, has made it an attractive option for applications in biology, physics, and materials science. The main challenge, however, lies in the loss of phase information during detection, as conventional cameras are sensitive only to the intensity (or square modulus) of the light field. Thus, reconstructing the original object from such

measurements requires sophisticated numerical algorithms, often based on Fourier optics. [2]

A major leap in the development of lensless microscopy came with the invention of Gabor's in-line holography in 1948, where the introduction of a reference beam allowed for the interference with the diffracted beam, effectively encoding both amplitude and phase information directly into the recorded diffraction pattern. This enabled more precise reconstructions and removed the need for complex optical setups, thus simplifying both the experimental implementation and data analysis. Today, this technique remains central to lensless microscopy applications and is widely employed in studying biological samples, including cell structures, live organisms, and microbe motility. In addition to the advantages of simplicity and cost-effectiveness, lensless microscopy has also gained attention due to its ability to achieve both high resolution and large field-of-view (FOV) imaging, a combination that has traditionally been difficult to achieve in conventional microscopy systems. A key limitation of classical optical microscopes is the trade-off between resolution and FOV—improving one typically sacrifices the other. This trade-off becomes especially problematic in biomedical applications, where a large FOV is often essential for examining dynamic processes such as cell motility, tissue cultures, or organism development. Lensless systems, however, allow for high-resolution imaging over large areas without such compromises. [3-4]

One of the most notable aspects of lensless in-line holography is its ability to capture depth information in a single acquisition, bypassing the need for multiple projections required by other 3D imaging techniques like tomography. By recording a single hologram, the three-dimensional structure of a sample can be reconstructed with both amplitude and phase information of the exit wave, providing valuable insight into the refractive index variations of biological materials. This is particularly beneficial in dynamic biological studies, where real-time imaging and minimal radiation exposure are crucial.

The high versatility of lensless microscopy has spurred considerable interest in its use for in vivo imaging, especially for label-free applications. This technique has found a wide array of applications in biology, ranging from cell component analysis (such as cytoplasm, nucleus, and nucleolus) to live imaging of embryos, and even motility studies of microorganisms such as cyanobacteria. The ability to perform live, label-free imaging with minimal invasiveness makes it an ideal choice for observing living biological samples under physiological conditions, which is often a limitation of fluorescence-based imaging techniques that require dyes or markers. In particular, the low radiation dose required for holographic imaging makes it an attractive solution for tracking biological processes in real-time without causing significant disruption to the sample. [5]

Another factor contributing to the appeal of lensless on-chip microscopy is its compactness and portability. Traditional compound microscopes, with their complex lenses, mechanical alignment systems, and bulky optical components, are often impractical for field-based or point-of-care applications. In contrast, lensless on-chip microscopes utilize simple, small-scale sensors (such as CCDs or CMOS chips) and require no additional lenses or mechanical components. The sample is placed directly above the image sensor chip, typically less than 1 mm away, and is illuminated by a partially coherent light source. The resulting hologram can be used to digitally reconstruct both amplitude and phase images of the sample, offering a significant reduction in system complexity and cost. The decoupling of resolution and FOV in lensless on-chip microscopes represents another major advantage. In conventional microscopy systems, improving resolution often reduces the observable sample area, but with lensless systems, the resolution is determined by the pixel size of the image sensor and the signal-to-noise ratio, while the FOV corresponds to the active area of the sensor chip. This allows for both large-area imaging and high-resolution observation, providing new possibilities for a range of applications. These systems can achieve FOVs ranging from 20–30 mm^2 in CMOS-based devices to up to 10–20 cm^2 with CCD-based systems, far exceeding the limited FOV of conventional microscopes. Beyond its simplicity, compactness, and versatility, lensless microscopy also benefits from the fact that the diffraction-based imaging method enables three-dimensional (3D) reconstructions with a large depth-of-field (DOF). This feature allows for the examination of samples at different depths without requiring physically moving the sample or the imaging system. Digital refocusing can generate multiple reconstruction planes within the sample volume, providing detailed 3D information of the structure. The ability to maintain a large DOF also helps mitigate issues such as optical shadowing, a

common concern in traditional microscopy. As lensless on-chip microscopy continues to evolve, it has demonstrated vast potential across diverse applications, including disease diagnosis, microbial monitoring, water-quality testing, 3D motion tracking of biological samples, and even high-energy particle analysis. The computational power available today enables sophisticated imaging and reconstruction algorithms, which further enhance the capabilities of lensless systems. The continued miniaturization of components, coupled with the development of new algorithms for faster and more accurate reconstructions, promises to expand the use of lensless microscopy in a wide array of fields. In this manuscript, we present an overview of the principles, capabilities, and applications of lensless on-chip microscopy. We focus on its use in biological imaging, particularly in label-free, live imaging of dynamic processes. The paper also explores recent advancements in 3D reconstruction techniques, the integration of computational algorithms, and the prospects for future improvements in system design and performance. Through several examples, we demonstrate the wide range of applications made possible by this innovative imaging modality, highlighting its potential to revolutionize both laboratory-based and field-based microscopy [6-8].

2. Material & methods

2.1 Olympus Magnus MX21i/CX21i microscope

The Olympus Magnus MX21i/CX21i microscope series represents a range of advanced optical instruments widely used in laboratory research, education, and industrial applications. These microscopes are specifically designed to deliver high-quality imaging, enabling precise observation and analysis of specimens across diverse scientific fields such as biology, material science, and medical research. They incorporate high-quality optical components that produce sharp, clear, and high-resolution images, often supported by advanced infinity-corrected optics that minimize optical aberrations and enhance imaging accuracy. The system offers a broad magnification range, typically from 4× to 100×, with the possibility of achieving higher magnifications using oil immersion objectives, thereby accommodating both low- and high-resolution studies. The illumination system in these microscopes is generally based on energy-efficient LED technology, which provides stable and bright light with adjustable intensity to improve contrast and specimen visibility. Ergonomic considerations are also integral to the design, including adjustable eyepieces and user-friendly focusing controls that reduce strain during prolonged usage. Additionally, many models support camera integration, allowing real-time imaging and image capture through compatibility with Olympus digital cameras and other imaging systems. The mechanical stage ensures precise specimen movement, facilitating accurate focusing and observation, and in some models, built-in focusing mechanisms further enhance operational convenience. The working principle of the Olympus Magnus MX21i/CX21i microscope is based on the transmission of light through the specimen. Light from the base illumination source passes through the sample and is then collected by the objective lens, which provides the primary magnification. Interchangeable objective lenses, typically including 4×, 10×, 40×, and 100×, allow flexibility in magnification levels. The magnified image is subsequently transmitted to the eyepiece for visualization, or to an attached camera system for digital imaging. The focusing mechanism, consisting of coarse and fine adjustment knobs, enables precise control over the distance between the objective lens and the specimen to achieve a sharp image. Additional components such as the condenser lens focus light onto the specimen to enhance contrast and resolution, while optional filter systems can be used to further improve image quality or produce specific imaging effects [8–10].

Figure 1. Olympus Magnus microscope

2.2 Lensless Microscope:

Comparative Study Of Novel Lensless Microscope With Marketed Trinocular Digital Microscope

A lensless microscope is an imaging system that captures diffraction or shadow patterns generated when light interacts with a specimen directly onto a digital image sensor, such as a CMOS or CCD sensor. Unlike conventional microscopes, it does not use optical lenses; instead, it relies on computational algorithms to reconstruct high-resolution images from the recorded patterns. The system primarily consists of a light source, typically an LED or laser, which illuminates the sample either from above or below; a sample platform where the specimen is placed very close to the image sensor; an image sensor that records the diffraction or shadow pattern; and a computational unit that processes the captured data. Advanced algorithms such as back-propagation, Fourier transforms, phase retrieval techniques, and, in some cases, machine learning are employed to reconstruct the final magnified image.

The working principle of a lensless microscope involves illuminating the sample with coherent or incoherent light, resulting in the formation of diffraction patterns or shadows on the sensor instead of a focused image. These raw patterns are then computationally processed using digital holography and phase retrieval methods to generate a high-resolution reconstructed image. This approach eliminates the need for complex optical components, making the system compact, cost-effective, and suitable for portable applications [11–13].

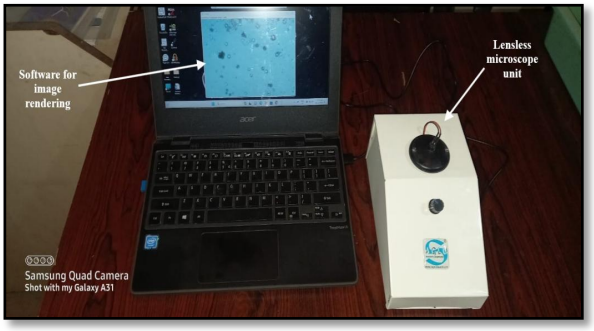


Figure 2 Lens less microscope

The methodology of the present study is divided into four major components: (i) development of the nano optical fiber-based lensless microscope, (ii) calibration, standardization, and validation of the developed system, (iii) development and validation of software, and (iv) comparative evaluation with a standard marketed microscope.

The development of the nano optical fiber-based lensless microscope involved the fabrication of optical nanofibers using materials such as glass, plastic, and photonic crystal fibers. The fabrication process was carried out using Modified Chemical Vapor Deposition (OF-CVD), which enabled the deposition of thin films and functional coatings on the fibers. These modifications improved light transmission, enhanced durability, and optimized the fibers for efficient illumination in the lensless system. The complete microscope system was assembled as a compact on-chip imaging platform within a CNC-machined aluminum housing to ensure structural stability and precision. The system integrated a CMOS sensor, nano optical fiber, optical fiber holder, and a micro-sample placement platform, enabling high-resolution imaging without conventional lenses.

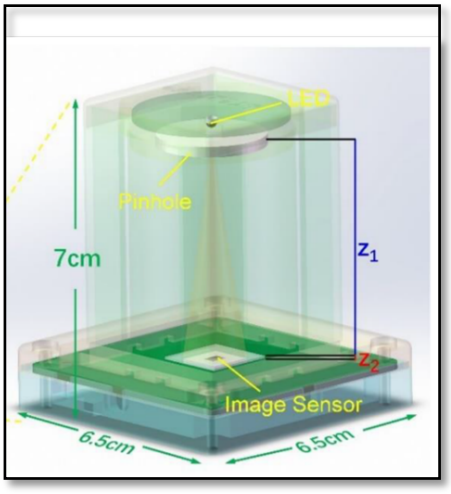
Calibration, standardization, and validation were performed to ensure the reliability and reproducibility of the system. Calibration involved optimizing alignment and imaging parameters to minimize errors and ensure accurate image acquisition. Standardization was achieved by establishing

operating protocols comparable to those used in conventional microscopes, with the Olympus microscope serving as a reference system. The performance of the lensless microscope was benchmarked using standard pharmaceutical samples such as drug powders, emulsions, suspensions, microencapsulated granules, liposomes, crystalline forms, nanoparticles, polymeric microparticles, and microspheres. Validation was conducted by comparing results obtained from the lensless microscope with those from the conventional system. Quantitative evaluation included the use of edge spread function (ESF) analysis and full width at half maximum (FWHM) measurements, yielding an overall resolution of approximately 1.4 µm and an improved ESF resolution of about 0.8 µm. [14]

The development of software for the lensless microscope was carried out using a Python-based platform designed for image acquisition, processing, and report generation. The software featured a user-friendly graphical interface, predefined templates for standardized reporting, and export capabilities in formats such as PDF. It enabled manual data entry, formatting, and efficient report generation, thereby enhancing workflow productivity. The system was tested using various pharmaceutical and biological samples, including cancer cell lines, micro-sponge particles, and plant cells, and the generated images were compared with those from conventional microscopy to validate accuracy.

Software validation was performed through multiple testing approaches. Functional testing ensured that all features operated according to specifications, while performance testing evaluated response time, throughput, and system efficiency under different conditions. Usability testing assessed the ease of use and user experience, and compatibility testing verified operation across different devices and environments. Security testing identified potential vulnerabilities, while interface testing ensured proper communication between system components. Reliability testing confirmed system stability and error-handling capabilities. Additional evaluations included documentation testing, regression testing, acceptance testing, maintainability testing, scalability testing, and compliance testing to ensure adherence to pharmaceutical industry standards and regulatory requirements. [15]

Finally, a comparative study was conducted between the developed lensless microscope and a standard marketed trinocular microscope (Olympus CX21i). The comparison focused on key performance parameters such as image quality, resolution, field of view, portability, and ease of use. Image quality assessment involved evaluating clarity and the ability to resolve fine details. Field of view analysis indicated that the lensless microscope provided a significantly larger imaging area. Portability evaluation highlighted the compact and lightweight nature of the lensless system, making it suitable for field applications. Ease of use was assessed based on operational complexity, where the lensless system demonstrated simplified hardware requirements despite reliance on computational processing. Overall, the comparative study indicated that the lensless microscope offers performance comparable to conventional systems, with additional advantages in portability and cost-effectiveness.



Lensless microscope

2.3 Calibration, Standardization, and Validation of Lensless Microscope:

2.3.1. Calibration:

The lensless microscope will be calibrated to ensure precise and consistent measurements. Calibration procedures will be implemented to correct any potential deviations in the imaging system. This process will involve adjusting the microscope settings to achieve optimal alignment and focusing, thereby guaranteeing the accuracy of the captured images.

2.3.2. Standardization:

To ensure uniformity and

reproducibility in the results obtained from the lensless microscope, standard operating protocols will be established alike standard marketed microscope (Olympus microscope will be used reference). These protocols will guide the use of the microscope, ensuring that it performs consistently across different samples and conditions. The microscope's performance will be benchmarked against known reference samples such as **drug powder, emulsion, suspension, microencapsulated granules, liposomes, crystalline drug forms, nanoparticles, polymeric microparticles, microspheres** to validate its operational standards by comparing with standard marketed microscope (Olympus microscope will be used reference). [16]

2.33. Validation:

A comprehensive validation process will be conducted to confirm the reliability and accuracy of the lensless microscope. This process will involve testing the microscope with a variety of pharmaceutical samples under different conditions to assess its effectiveness and robustness. The validation will include a comparison of results obtained from the lensless microscope with those from conventional microscopes to verify accuracy and performance. Specific metrics, such as overall resolution and intensity profiles, will be quantified using the edge spread function (ESF). The Full Width at Half Maximum (FWHM) of the contrast derivative or the 10–90% variation of a complete step will be calculated, with an expected resolution of around 1.4 μm and an improved ESF resolution of approximately 0.8 μm.

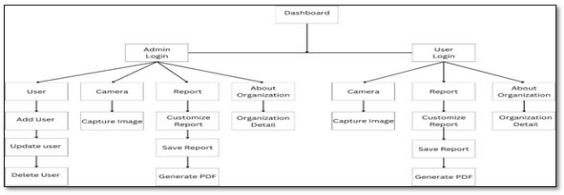
3. Development and Validation of Software for Lensless Microscope:

The development of software for the lensless microscope will be based on a Python platform, designed specifically for the analysis of microscopic samples. This Python-based software will serve as a tool for generating microscopic reports, offering a user-friendly interface for manual data entry and report creation. The software will enable users to input observations and data manually, with predefined templates for consistent report formatting. It will support functionalities such as data entry, formatting, and report generation, all within a single platform.

Key features of the software will include:

- User-Friendly Interface: An intuitive graphical interface that simplifies the process of report creation.
- Predefined Templates: Standardized templates for consistent formatting of reports.
- Export Options: Ability to save reports in various formats, including PDF.

The software will be developed to enhance productivity and efficiency in microscopic analysis workflows, providing a convenient tool for researchers and practitioners. The system will be tested with various pharmaceutical samples such as cancer cell lines, micro-sponge particles, and plant cells. The images generated by the lensless microscope will be compared with those obtained from traditional microscopes using the same samples, ensuring the accuracy and validity of the final micro images.



Software system flowchart

- **Software Validation Parameters:**

1. Functional Testing:

- Objective: To verify that all functionalities of the software perform as intended.

- Approach: The software will be tested against the specified requirements to ensure that each feature operates correctly. This includes testing individual modules, user interfaces, and the overall system to confirm that the software meets its design specifications.

2. Performance Testing:

- Objective: To assess the software's performance metrics under various conditions.

- Approach: The software's response time, throughput, and resource utilization will be measured under normal and peak load conditions. This will help determine if the software can handle high-demand scenarios without compromising performance.

3. Usability Testing:

- Objective: To evaluate the software's user-friendliness and ease of use.

- Approach: Usability testing will involve real users interacting with the software to assess its intuitiveness and accessibility. Feedback will be gathered to identify any usability issues and improve the user experience.

4. Compatibility Testing:

- Objective: To ensure the software functions correctly across different environments.

- Approach: The software will be tested on various devices, operating systems, and browsers (if applicable) to verify compatibility. This ensures that users can access and use the software regardless of their technological environment.

5. Security Testing:

- Objective: To identify and mitigate potential security vulnerabilities.

- Approach: Security testing will involve assessing the software for common security threats, such as data breaches, unauthorized access, and data corruption. The software will be evaluated to ensure that it properly handles data protection and privacy in compliance with industry standards.

6. Interface Testing:

- Objective: To validate the interactions between software components and external systems.

- Approach: This testing will verify the accuracy and reliability of APIs, data formats, and communication protocols used by the software. Ensuring seamless interaction between components and external systems is critical for maintaining overall system integrity.

7. Reliability Testing:

- Objective: To determine the software's stability and error-handling capabilities.

- Approach: Reliability testing will involve running the software under specified conditions to ensure it performs consistently and can recover from errors. This includes testing for software crashes, data corruption, and other failure scenarios.

8. Documentation Testing:

- Objective: To ensure all user

manuals, help guides, and documentation are accurate and comprehensive.

- Approach: Documentation testing will involve reviewing all instructional materials associated with the software to verify that they are complete and correctly reflect the software's functionality. This ensures users can effectively utilize the software.

9. Regression Testing:

- Objective: To ensure new code changes do not negatively impact existing functionalities.

- Approach: After any software updates or modifications, regression testing will be conducted to verify that the software's existing features continue to function correctly. This helps prevent the introduction of new bugs during the software's lifecycle.

10. Acceptance Testing:

- Objective: To validate the software against user requirements and business processes.

- Approach: Acceptance testing will involve stakeholders and end-users to ensure the software meets their needs and expectations. This final step before deployment confirms that the software is ready for use in a real-world environment.

11. Maintainability Testing:

- Objective: To assess the ease of maintaining and updating the software.

- Approach: The software will be evaluated for code readability, modularity, and ease of bug fixing. Maintainability testing ensures that the software can be efficiently managed and updated over time.

12. Scalability Testing:

- Objective: To evaluate the software's ability to scale and handle increased loads.

- Approach: Scalability testing will involve simulating scenarios where the software needs to handle a growing number of users or data volume. This testing ensures the software can scale without degrading performance.

13. Compliance Testing:

- Objective: To ensure the software complies with pharmaceutical industries standards and regulations.

- Approach: The software will be reviewed and tested against applicable standards and regulations, such as data protection laws, industry-specific guidelines, and technical standards. Compliance testing ensures that the software operates within legal and regulatory boundaries.

4. Validation and comparative study of developed lensless microscope with standard marketed microscope:

A comparative study between a standard marketed microscope—specifically, the Olympus Pathological Research Microscope, Model: CX 21i Trinocular—and the developed lensless microscope will focus on evaluating key aspects such as image quality, resolution, field of view, portability, ease of use, and potential applications by accuracy and precision ≈ 100.

Performance validation:

Image Quality:

- The study will compare the resolution and clarity of images produced by both microscopes, assessing how well each microscope resolves fine details.

Field of View:

- The field of view offered by both microscopes will be evaluated. It is anticipated that the lensless microscope might provide a much

larger field of view up to 100X magnification compared to the standard microscope.

Portability:

- The physical dimensions, weight, and power requirements of both microscopes will be discussed. It is expected that the lensless microscope will be generally more portable, which could be advantageous for field applications.

Ease of Use:

- The complexity of setup and operation for both microscopes will be compared. While the lensless microscope may require more computational processing, it could potentially be easier to use in some aspects [18-21].

Result discussion:-

3.1 Comparative study of Lensless microscope Vs Olympus Magnus Microscope:

Various Pharmaceutical samples are taken to ensure the credibility of the lensless microscope as compared to the traditional Olympus microscope. In this study different pharmaceutical samples of varying particle sizes are seen under the traditional microscope as well as the lensless microscope and the output is compared.

The steps in comparative study are as follows:

1. **Preparation of slides**
2. **Observing the prepared slide under the Olympus microscope**
3. **Observing the pharmaceutical sample under the Lensless microscope**

1. **Preparation of slides:**

Firstly, the slides are washed with alcohol and air dried. The sample is then loaded on the slide, depending upon the nature of the sample paraffin oil is used if necessary. The cover slip is mounted upon the sample.

2. **Observing the prepared slide under the Olympus microscope:**

The prepared slide is then observed under the microscope under the suitable magnification. The image is captured with the help of microscope camera and software.

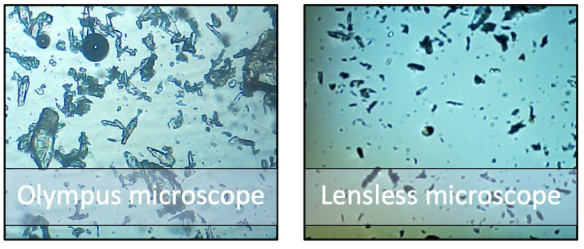
3. **Observing the pharmaceutical sample under the Lensless microscope:**

When observing under lensless microscope the sample is directly placed on the sensor of the microscope, if the sample is solid in nature paraffin oil is used which aids in better resolution. The sample is directly observed on a screen and an image is taken with the help of software for the comparative studies.

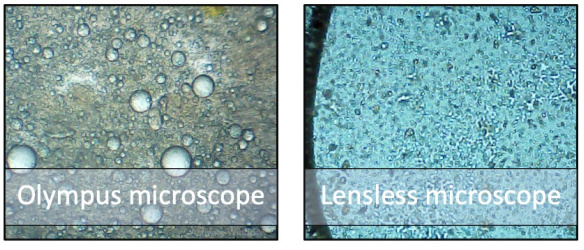
Sr. no.	Pharmaceutical sample	Type of sample	Typical size range	Pharmaceutical studies
1	Drug Powder	Solid	1 µm to 50 µm	Suitable for observing particle size and shape.
2	Emulsion	Liquid	0.1 µm to 10 µm	Suitable for droplet size distribution analysis.
3	Suspension	Liquid/ Solid	0.5 µm to 100 µm	Suitable for analyzing dispersed particles.
4	Microencapsulated Granules	Solid (Coated)	10 µm to 500 µm	Suitable for observing encapsulation uniformity.
5	Liposomes	Liquid (Vesicles)	50 nm to 5 µm	Suitable for larger liposomes, smaller ones need higher magnification.
6	Crystalline Drug Forms	Solid	1 µm to 100 µm	Suitable for examining crystal morphology.
7	Nanoparticles	Solid/Liquid	10 nm to 1 µm	Not suitable for observing nanoparticles under 100X.
8	Polymeric Microparticles	Solid	1 µm to 100 µm	Suitable for assessing particle size and shape.
9	Microspheres	Solid	1 µm to 200 µm	Suitable for checking uniformity in size distribution.
10	Tablet Granules	Solid	100 µm to 1 mm	Suitable for observing granule size.
11	Powder Blend	Solid	10 µm to 500 µm	Suitable for assessing homogeneity of the blend.

Table 1- shows Comparative study of Lensless microscope Vs Olympus Magnus Microscope of different pharmaceutical sample

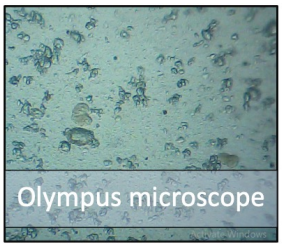
a. Drug powder –

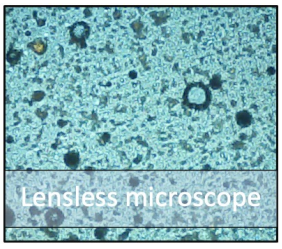


b. Emulsion –

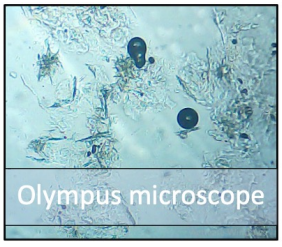


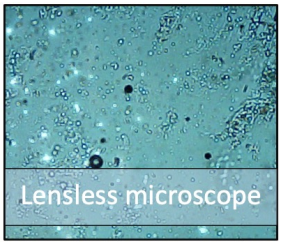
c. Suspension –



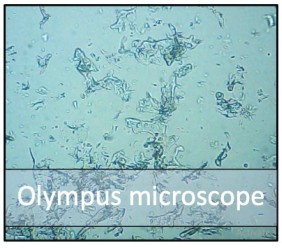


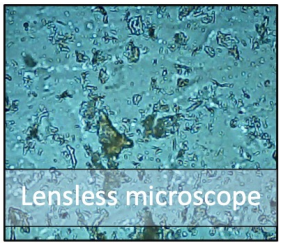
d. Liposomes –



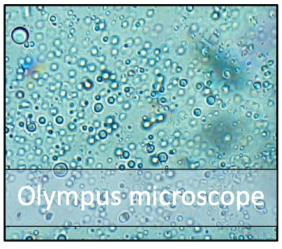


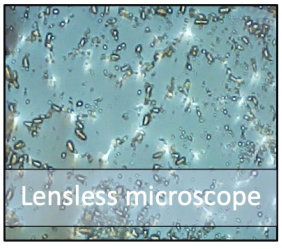
e. Crystalline Drug Forms –



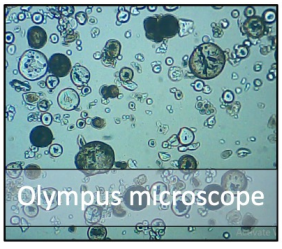


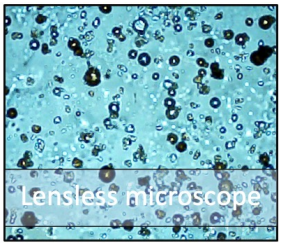
f. Polymeric Microparticles –



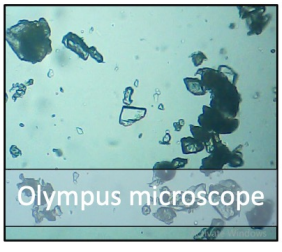


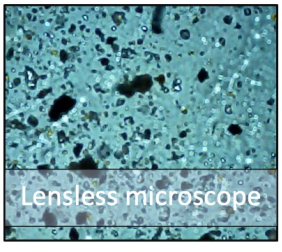
g. Microspheres –



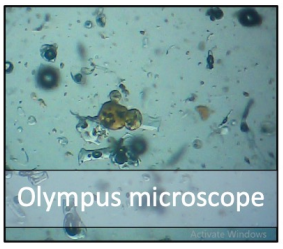


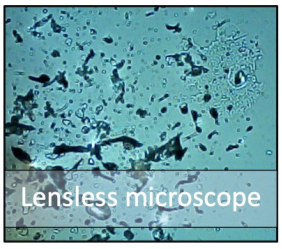
h. Tablet Granules –





i. Powder Blend –





The result obtained after observing the different samples under both the microscopes suggests that the lensless microscope is equally good as the Olympus microscope which is used as a standard for this experiment, and the lensless microscope having handling advantages along with its portability makes it fairly better microscope for emergency testing and other microscopical applications.

Applications of lensless microscope:

1. Point-of-Care Medical Diagnostics

- **Applications**: Lensless microscopes enable rapid detection of blood parasites (e.g., *Plasmodium*), urine pathogens, sperm motility, and cell abnormalities.
- **Example**: The LUCAS platform employs lensless on-chip imaging to identify and count cells, aiding in diagnostics for diseases like malaria and tuberculosis [22-25].

2. Field and Resource-Limited Settings

- **Applications**: Due to their portability and low power consumption, lensless microscopes are suitable for use in developing countries and remote areas.
- **Example**: A lensless digital microscope, weighing approximately 38 grams, can be attached to a cellphone, enabling diagnostics in resource-limited settings.

3. Environmental Monitoring

- **Applications**: Lensless microscopes can monitor air and water quality by detecting microorganisms and particulates.
- **Example**: Lensless digital holographic microscopy has been applied to environmental monitoring, enabling high-resolution imaging of specimens in compact devices.

4. Lab-on-a-Chip Integration

- **Applications**: Combining lensless microscopy with microfluidics allows for real-time tracking of single-cell behaviour and high-throughput screening.
- **Example**: Lensless on-chip imaging platforms, such as LUCAS, facilitate high-

throughput cell biology and medical diagnostics [25-31].

5. Education and Citizen Science

- **Applications**: Affordable and compact lensless microscopes serve as educational tools and enable citizen science projects.
- **Example**: Lensless microscopy platforms have been developed for educational purposes, allowing students to explore microbiology and microscopy without expensive equipment.

6. Drug Discovery and Biological Research

- **Applications**: Lensless microscopes facilitate monitoring of cell growth, morphology, and dynamics without interfering with the sample.
- **Example**: Lensless on-chip imaging modules have been used for optical monitoring of adherent growing mammalian cells, supporting drug testing and toxicology studies.

7. Smartphone-Based Imaging

- **Applications**: Mobile lensless microscopes can transform smartphones into diagnostic tools, enabling telemedicine and remote diagnostics.
- **Example**: Lensless digital microscopy on a cellphone allows for imaging of micro-particles and cells, with potential applications in global health diagnostics [32-34].

8. Space Exploration and Astrobiology

- **Applications**: Compact and low-power lensless microscopes are ideal for experiments on space missions, such as studying microbial growth in microgravity.
- **Example**: Lensless microscopy platforms have been considered for space missions to study microbial growth in microgravity [12-16].

5. CONCLUSION

The developed nano optical fiber-based lensless microscope demonstrates comparable performance to a standard marketed trinocular digital microscope. It achieves high-resolution imaging (~1.4 µm) with improved edge-spread resolution (~0.8 µm), while offering significant advantages such as portability, low cost, large field of view, and minimal optical complexity. The integration of computational imaging and software-based analysis enhances its usability and reliability. These features make the lensless microscope a promising tool for pharmaceutical analysis, biomedical research, and point-of-care diagnostics, especially in resource-limited settings.

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