Bioprocessing Market Research

Process Analytical Technology (PAT) Market Outlook

PHOTON VENTURES

DEEP TECH FUND for INTEGRATED PHOTONICS

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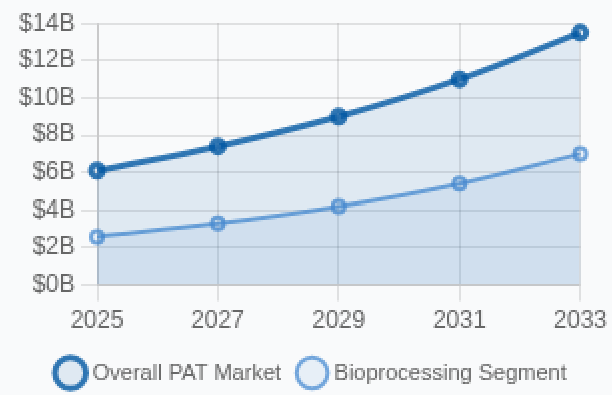
Executive Summary

- Process Analytical Technology (PAT) enables **real-time monitoring & control** in bioprocessing and chemical industries
- **Optical techniques**, especially Raman spectroscopy, dominate due to their specificity and non-invasive, real-time capabilities
- Global PAT market valued at **$6.1B in 2025**, projected to reach **$13.5B by 2033** (CAGR of 10%); bioprocessing segment growing at 13%
- Growth drivers: stricter regulations, personalized medicine demand, and need for higher process efficiency and quality
- Current challenges: **high system costs**, integration complexity, and stringent GMP compliance requirements
- **Photonic Integrated Circuits (PICs)** offer breakthrough potential, making PAT systems smaller, cheaper, more robust, and scalable
- M&A activity remains steady with exits at SME stage and stable multiples (6x); strategic acquisitions driven by capability expansion

PAT Market Growth Trajectory



Global PAT Market Size ($ Billions)

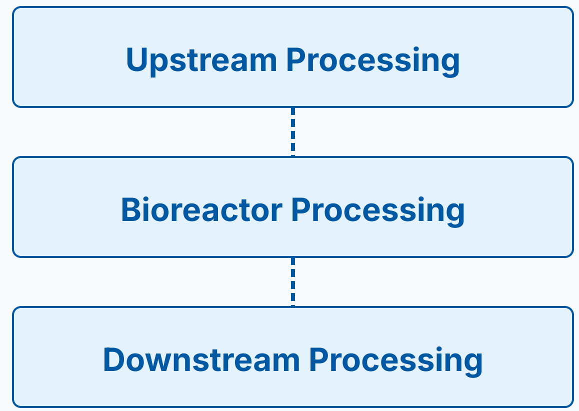
Strategic Implication

Strong technology-market fit for photonics in PAT, but successful ventures must navigate challenging market dynamics between niche applications and the highly regulated pharmaceutical sector.

Process Analytical Technology (PAT) is a sensor system used to monitor processes

Process Analytical Technology (PAT) serves as a critical enabler for real-time monitoring and control in both bioprocessing and chemical manufacturing industries

- PAT systems help manufacturers improve quality, reduce variability, and increase efficiency through **continuous process monitoring** rather than traditional endpoint testing
- In bioprocessing specifically, PAT addresses **unique challenges**:
  - Higher intrinsic variability due to living cell behaviour
  - More stringent regulatory requirements
  - Growing demand for process intensification
- The industry is shifting toward **Industry 4.0 automation** with integrated PAT solutions that enable data-driven process control



PAT integration across the bioprocessing value chain enables continuous monitoring and improved quality control

Key Market Driver

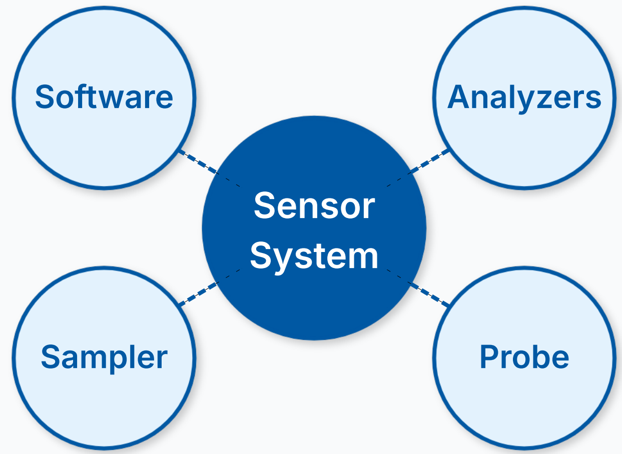
PAT adoption is favourable to ensure product quality and consistency across manufacturing batches.

Technology Landscape

Process Analytical Technology (PAT) systems and sensor technologies for real-time monitoring and control in bioprocessing

PAT is able to measure the variability of a process

- **Process Analytical Technology (PAT)** is a sensor system that monitors process variability by measuring critical process variables
- Key benefits of PAT implementation:
  - Real-time insights into process status
  - Active process control based on measured variables
  - Faster process development cycles
  - Higher quality product formulation
- PAT is **particularly critical** for bioprocessing where:
  - Living cells create inherent process variability
  - Conditions may require adjustment during production



The PAT sensor system integrates four core components in one sensor system, enabling real-time process monitoring and control through data collection, analysis, and feedback

Evolution of PAT

Conventional
Manual sampling and offline analysis with significant delays

Modern
Automated, real-time monitoring with integrated control systems

PAT is agnostic to the application

Upstream Processing → **Downstream Processing**

Media Preparation → Inoculation → Bioreactor → Capture → Polishing → Formulation

- **PAT applications span the entire process**, enabling continuous monitoring and real-time control at multiple stages
- Bioprocessing and chemical processing share similar overall structures, but PAT implementation differs based on process characteristics
- PAT is typically **adopted earlier in chemical processing** due to less complex integration requirements

Comparison Area	Bioprocessing	Chemical Processing
Materials	Living cells (variable)	Chemicals (consistent)
Conditions	Mild, longer process time	More extreme, shorter process time
Downstream	Intensive, stringent GMP requirements	Less complex purification
Variability	Higher intrinsic variability	Lower variability, more repeatable
PAT Impact	Critical for process control	Enhances efficiency, more established

PAT is a sensor system with four core elements

- Process Analytical Technology (PAT) is a comprehensive **sensor system** consisting of four main elements working together to enable real-time process monitoring and control

1. Analyzer

Measures chemical or physical properties of materials being produced, analyzing samples to ensure process control

2. Probe

Interfaces directly with the process media, sensing conditions and converting readings into electrical signals for digitization

3. Sampler

Automated systems that withdraw representative portions of process fluid at predefined intervals or on-demand

4. Software

Transforms raw data into actionable insights, enabling process prediction and providing feedback for control

PAT Sensor System Process Flow

Strategic Impact

An integrated PAT sensor system enables real-time process monitoring and control, significantly reducing batch variability while improving product quality, consistency, and manufacturing efficiency.

There are different type of sensor systems based on different technological principles

Sensor Type	Principle	Advantages	Challenges
Electrochemical	Electrical potentials due to chemical reaction	Easily miniaturized and placed in small spaces	Requires contact with media and needs reference electrode
Optical	Light interaction with sample (Raman, NIR, Fluorescence, Dynamic Light Scattering, Refractive index)	No sampling needed; obtains molecular fingerprint; multiplexed measurements	Cannot differentiate between dead and living cells
Biosensor	Biological reaction	Very selective for specific targets	High oxygen consumption; sensitive to buffer capacity and pH
Capacitance	Change in electrical capacity	Measures viable biomass via intact cell membranes	Cannot measure dead cell count
Impedance	Resistive and capacitive behavior	Can distinguish between living and dead cells	Affected by temperature and ionic strength variations
Temperature	Temperature change	Simple measurement with resistance temperature detector	Limited to temperature measurements only
Calorimetry	Heat exchange	Measures overall heat production	Difficult to isolate heat from metabolism vs. other sources
Magnetic	Magnetic fields	Capable of compositional analysis	Easily influenced by external magnetic fields
Soft	Hardware and software integration	Can predict process variables	Cannot handle unforeseen process changes with high variance
Piezo-electrical	Pressure change	Accurate measurement of pressure changes	Cannot measure constant or slowly changing pressure

Key Insight

Optical sensors can measure the broadest range of process variables (7 out of 10), making them the most versatile PAT solution for comprehensive Bioprocess monitoring.

Selection Criteria

The optimal sensor system depends on specific process variables requiring measurement, integration complexity, and cost considerations for the particular application.

The different sensor systems measure different process variables

Process Variable	Electrochemical	Optical	Biosensor	Capacitance	Impedance	Temperature	Calorimetry	Magnetic	Soft sensor	Piezo-electrical
pH	✓	✓	✓	–	–	–	–	–	✓	–
Temperature	–	✓	–	–	–	✓	✓	–	✓	–
Dissolved Oxygen	✓	✓	✓	–	–	–	–	–	✓	–
Cell Count	–	✓	–	✓	✓	–	–	–	✓	–
Biomass	–	✓	✓	✓	✓	–	✓	–	✓	–
Glucose	✓	✓	✓	–	–	–	–	–	✓	–
Pressure	–	–	–	–	–	–	–	–	✓	✓
Media Components	–	✓	✓	–	–	–	–	✓	✓	–
Conductivity	✓	–	–	–	✓	–	–	–	✓	–
Product Quality	–	✓	✓	–	–	–	–	✓	✓	–

Key Insight

Optical sensors can measure the broadest range of process variables (7 out of 10), making them the **most versatile PAT solution** for comprehensive Bioprocess monitoring.

Selection Criteria

For complete process monitoring, a strategic combination of sensors is required, with optical technology (especially **Raman spectroscopy**) serving as the foundation supplemented by specialized sensors.

Raman Spectroscopy – Technology Spotlight

- **How it works:** Raman spectroscopy measures the inelastic scattering of light by molecules, creating a distinct "molecular fingerprint" that corresponds to specific vibrational modes of chemical bonds

Key Advantages

✓ **High molecular specificity** – Sharp, well-resolved bands enable distinction between structurally similar compounds

✓ **Real-time monitoring** – Enables continuous in-line process monitoring without sample preparation

✓ **Nondestructive & noninvasive** – Sample remains intact and uncontaminated during measurement

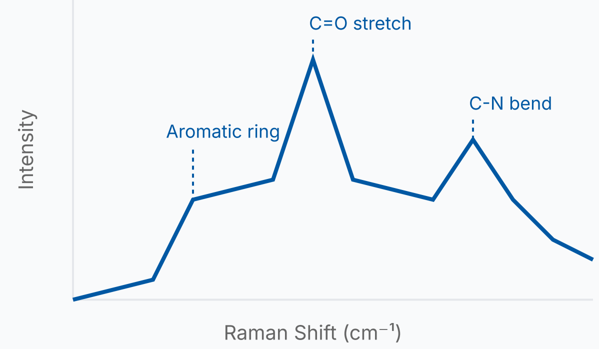
✓ **Minimal water interference** – Water is a weak Raman scatterer, ideal for aqueous bioprocesses

Key Challenge

⚠ **Cost** – Raman systems are typically more expensive ($50,000-$250,000) than other PAT technologies, creating a trade-off between quality and cost efficiency

Raman Spectrum of Paracetamol Derivative

Molecular fingerprint showing characteristic peaks



Raman spectroscopy creates a unique spectral "fingerprint" of molecular structures, enabling precise identification and quantification of compounds in complex biological media

Emerging Trend

Raman spectroscopy is gaining dominance in bioprocessing PAT due to its exceptional ability to distinguish structurally similar compounds in real time, especially in water-based bioprocesses where other techniques struggle.

Data & AI - Technology Spotlight

- **AI models** and data utilization now drive quality and throughput more than hardware alone; defensibility is shifting from proprietary hardware to **model quality**, data access, and seamless integration.

Software Development

- Legacy Process Analytical Technology (PAT) software is relatively simple; most PAT systems ship with integrated, proprietary software.
- Leveraging **soft sensors** and AI for real-time insights and automated set-point adjustments can unlock material value beyond traditional software + hardware combinations.
- Building these capabilities demands deeper expertise and tight co-designs between innovative hardware, modelling/ML, and controls engineering.
- Additional upside arises when players can **fuse data** beyond their own sensing platform. Combining inputs from multiple sensor types (including non-optical) and external systems to improve process understanding and control.

Soft Sensor Approaches

Model-driven

Based on physical, chemical, or biological models applied to calculate process variables

Data-driven

Based on relationships directly from process data to predict variables that cannot be measured directly

Soft Sensors

- **Soft sensors** (software sensors) function as add-ons to existing sensor systems.
- They combine hardware (sensor) and software (**algorithms/models**) to calculate dependent variables.
- These sensors provide **fast, indirect on-line monitoring** of targeted variables, enabling improved process control and **adding significant value** to quality.

PAT continues to face challenges

- **Scaling challenges:** Bioprocesses are highly variable; scaling from small to large bioreactors introduces more variability, making consistent PAT calibration difficult
- **High system costs:** Traditional PAT systems are expensive ($50,000 - $250,000), limiting multiple measurement points in larger bioreactors. Many companies invest heavily in PAT implementation projects, creating strong resistance to switching technologies despite potential improvements
- **Integration complexity:** Regulatory compliance (especially in biopharma) requires extensive validation, documentation, and often specialized expertise

Ideal Sensor Requirements

- Small, consistent form factor across all process scales
- Affordable pricing allowing multiple measurement points
- Simplified validation process with pre-established GMP compliance

Implementation Barriers

The industry faces significant implementation challenges due to cost, complexity, and regulatory barriers that slow adoption of advanced PAT systems, particularly in highly regulated environments.

New disruptive technologies must address these barriers while maintaining or improving measurement quality to gain market traction.

Building an optical spectrometer system on a Photonic Integrated Circuit (PIC)

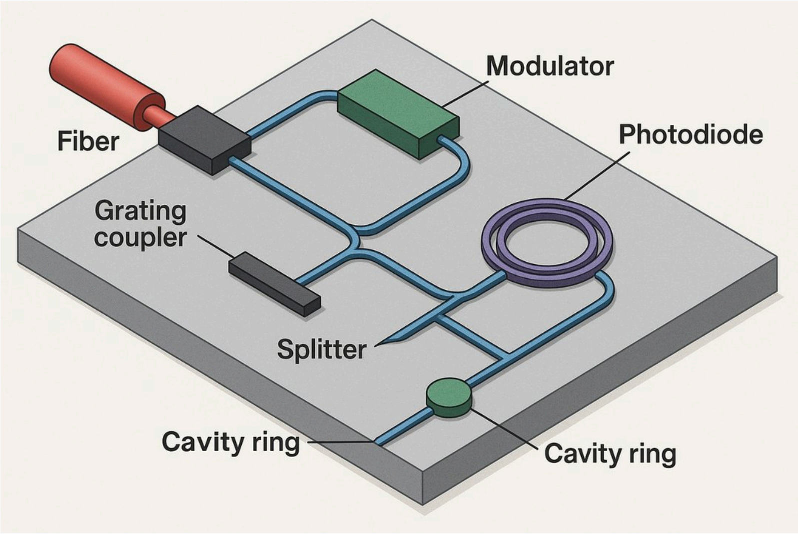
How a PIC-Based Spectrometer Works

A spectrometer on a PIC miniaturizes traditional optical analysis by integrating all components on a single chip. Instead of bulky optical benches, a PIC spectrometer guides light through microscopic waveguides to perform spectroscopic analysis.

These integrated spectrometers can analyze the chemical composition of samples with precision comparable to traditional systems, but at a fraction of the size and cost. The miniaturization enables deployment in environments where conventional instruments are impractical.

Spectrometer Workflow on PIC:

1. Light enters through grating couplers from sample or source
2. Waveguides direct light to wavelength-separation components
3. Filters or cavity rings select specific wavelengths
4. Photodetectors convert optical signals to electrical output



This PIC-based spectrometer integrates all optical components on a single chip. Light from a bioprocess sample enters through the fiber and grating coupler, travels through waveguides where splitters direct it to various analytical paths. Cavity rings act as wavelength filters for spectral analysis, while photodiodes convert specific light wavelengths into electrical signals for bioprocess monitoring.

PIC as Disruptive Solution for PAT?

- **Dramatic cost reduction:** PIC-based PAT systems can be 10 to 100 times cheaper than traditional systems, enabling widespread adoption across process points
- **Miniaturization advantage:** Dramatic reduction in physical footprint, enabling integration on a single chip and placement in small spaces that were previously inaccessible
- **Integration & multiplexed sensing:** Multiple components integrated on one chip allow for simultaneous monitoring of multiple process variables, significantly improving efficiency
- **Enhanced robustness:** Fewer moving parts result in greater stability and reliability in production environments
- **Scalability benefits:** Lower cost permits easier deployment of multiple sensors throughout the process, effectively addressing scaling challenges in bioprocessing
- **Single-use capability:** PICs enable disposable sensor options critical for pharma applications where sterilization is essential

But PICs are not always the best option

- **Established technology advantage:** The advantage of discrete systems is that they can often reach the market more quickly by leveraging off-the-shelf components within an established supply chain, combined with a broader market familiarity with how such systems operate.

PIC Technology delivers cost reductions

3-Year Total Cost of Ownership (TCO) comparison between conventional discrete-optics Raman systems and PIC-based Raman systems in two key application scenarios. This TCO does not take into account the costs of a software license.

A) Non-pharma (multi-use) — single bioreactor

Item	Discrete-optics Raman	PIC Raman (high-volume)
Analyzer (one-time)	$125,000 - $250,000	$20,000 (may drop further to $2500)
Probe / sensor hardware	$15,000 (reusable probe)	$500 (reusable PIC sensor module)
Maintenance & calibration (3yr)	$60,000 (~$20k/year)	$0 (no moving optics)
Consumables	$0	$0
3-yr TCO	**$325,000**	**$20,500**

94% cost reduction in multi-use markets

B) Bio-pharma (single-use) — 50 batches in 3 years

Item	Discrete-optics Raman	PIC Raman (high-volume)
Analyzer (one-time)	$125,000-250,000	$20,000 (may drop further to $2,500)
Probe / sensor hardware	$15,000 (reusable probe)	$500 (Reusable PIC sensor module)
Maintenance & calibration (3yr)	$60,000 (~$20k/year)	$0 (no moving optics)
Per-batch disposables	$15,000 = ($300 × 50) Disposable fitting	$7,500 = 50 × $150 (This may drop further to $50)
3-yr TCO	**$200,000-340,000**	**$28,000**

86-92% cost reduction in bio-pharma applications

Key Value Drivers

PIC technology delivers dramatic cost reductions through CMOS/PIC mass-manufacturing economies, elimination of bulky optics, and reduced maintenance requirements, while maintaining analytical performance.

Strategic Implications

The 85-94% TCO reduction represents a disruptive value proposition that could accelerate PAT adoption in both established markets and price-sensitive segments previously unable to justify conventional PAT systems.

Market Analysis

Comprehensive analysis of the global PAT market size, growth trends, segmentation, and strategic opportunities in bioprocessing and chemical industries

The Value Chain of PAT consists out of multiple key players

- The value chain is a set of key players and activities that are performed to get the technology to the market. The value chain of the PAT technology is shown below.

The value chain:

Established PAT companies and startups → Bio- / Chemical Processing companies (End users PAT) → Product

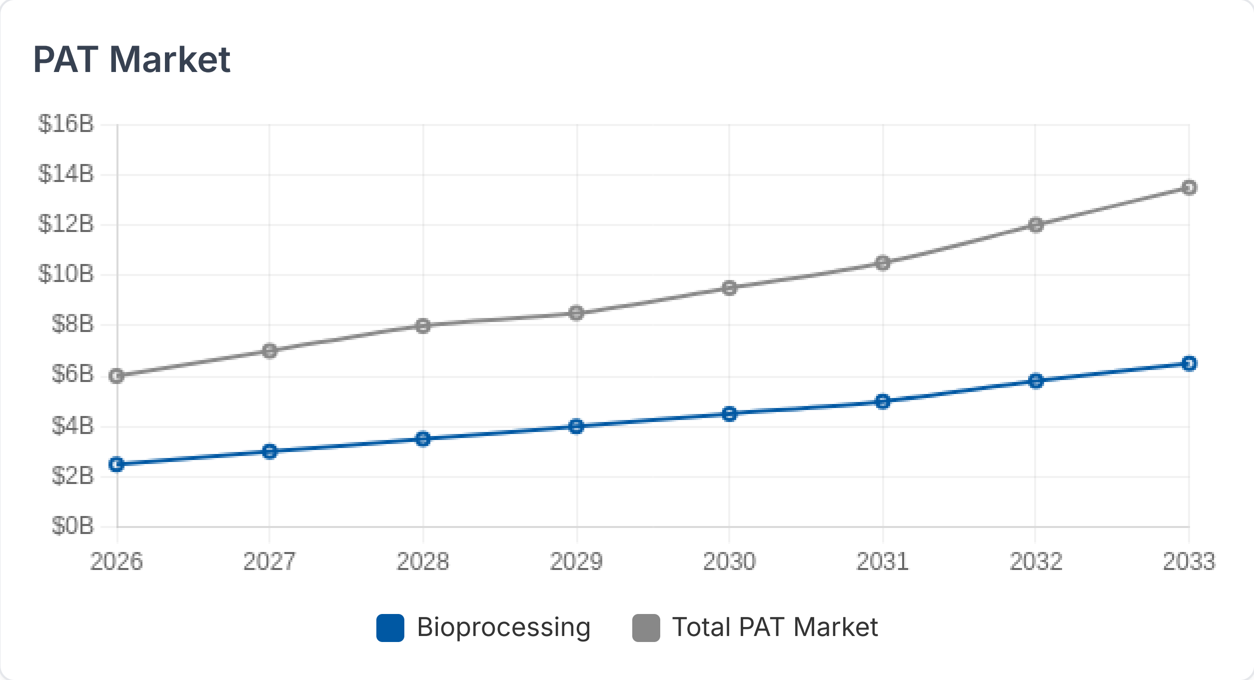
Regulatory instances

Go / No-Go

Key players:

Established PAT companies and startups	Regulatory compliance	Bio- / Chemical processing companies	Product
Thermo Scientific	EUROPEAN MEDICINES AGENCY	AMGEN	 Pharmaceuticals
inSpek	FDA	SARTORIUS	 Biofuels
timegate			 Fermented Foods
MyCellHub			

The PAT Market has multiple growth drivers



Growth Trajectory

Bioprocessing:
$2.5B → $6.5B (~12.7% CAGR)

Total PAT market:
$6.0B → $13.5B (~10.7% CAGR)

Key Market Growth Drivers

Regulatory Requirements

Stricter regulations driving demand for real-time quality control in manufacturing processes

Industry 4.0 Adoption

Shift toward automation technologies and digital transformation across manufacturing sectors

Personalized Medicine

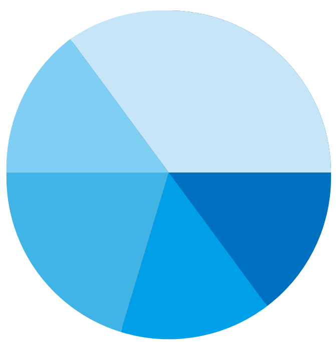
Growing demand for tailored therapeutic solutions requiring higher process efficiency and quality control

New End Markets

New markets offer opportunities for PAT to grow and create value

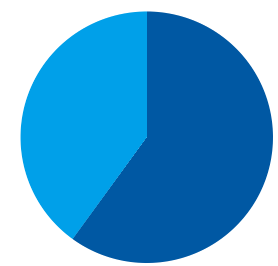
High-value pharmaceutical markets dominate, but emerging fields are growing

Total PAT Submarket



- Chemical & Petrochemical: 30%
- Pharmaceutical: 24%
- Biotechnology: 16%
- Food & Beverage: 15%
- Environmental: 9%
- Other: 6%

Bioprocessing PAT Submarkets



- Pharmaceutical: 60%
- Biotechnology: 40%

Bioprocessing Breakdown

Pharmaceutical Includes:

- Traditional medicines and drug manufacturing processes
- FDA- and EMA-regulated production
- Technologies needs to be GMP compliant
- Highest value segment
- High barrier to entry

Biotechnology Includes:

- Non-pharmaceutical sub markets (Biofuel, Food etc.)
- Small emerging markets
- Low barrier to entry

> We observed a pronounced market gap: contrary to what the data suggests, there appears to be no mature mid-market segment, with the landscape instead split between small but high-potential emerging markets and the dominant large pharma players.

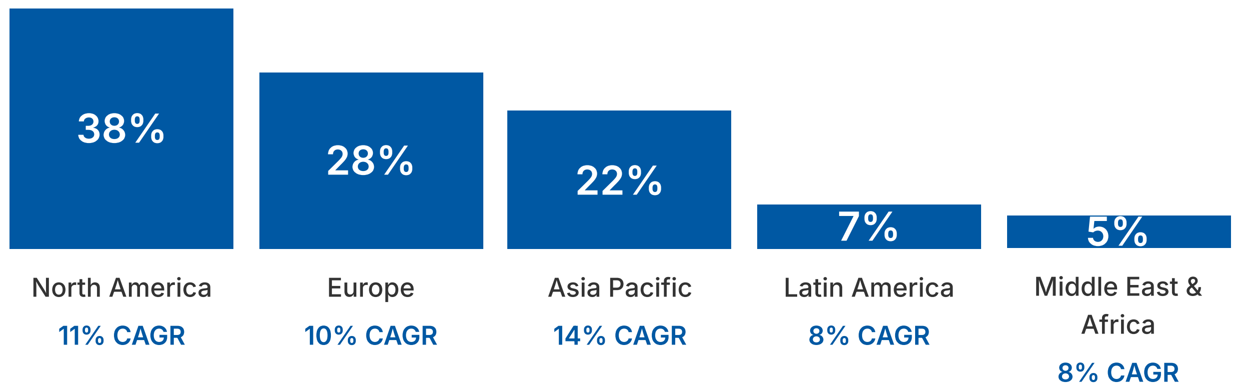
There are different growth opportunities across segments and regions

Product Segmentation

- Analyzers: 35%
- Probes: 30%
- Samplers: 20%
- Software & Services: 15%

All products are growing at similar rates

Geographic Segmentation



Technique Segment Insights

Spectroscopy dominates the technique segment, with NIR, Raman, and Fluorescence Spectroscopy leading the market.

- Non-invasive, non-destructive measurements
- High molecular specificity
- Growth: 11% CAGR

Monitoring Method Trends

In-line monitoring is the fastest-growing method, particularly in continuous manufacturing environments.

- Immediate feedback and control
- Enables Industry 4.0 integration
- Growth: 9% CAGR

Startup Landscape

Conventional Photonics

Timegate

Pulsed laser & time-gated detectors

Uses pulsed lasers and time-gated detectors to collect only fast Raman signals while filtering out slower fluorescence, providing clear molecular fingerprints for in-line bioprocess monitoring.

Gekko Photonics

Raman Spectroscopy focused on industrial practice

Develops inline Raman spectroscopy with self-cleaning probes installed directly in production lines, analyzing scattered light to identify chemical composition in real time.

ArgusEye

Nanoplasmonic Biosensor

Provides nanoplasmonic biosensors using metallic nanostructures where light detects refractive index changes from biomolecule binding for continuous, label-free protein measurement.

Integrated Photonics (PIC)

InSpek

Multi-sensor chip

Develops miniature photonic sensors based on integrated chips with waveguides guiding light through samples, enabling continuous in-line measurement of key molecules in a compact, robust format.

Firefly Sensing

Sensor based on the Refractive Index

Creates ultra-compact optical sensors measuring liquid properties like refractive index, concentration, and temperature in real time using light passing through liquid with tiny inline probes.

Perceptra

Miniature Raman Spectroscopy with a tunable laser

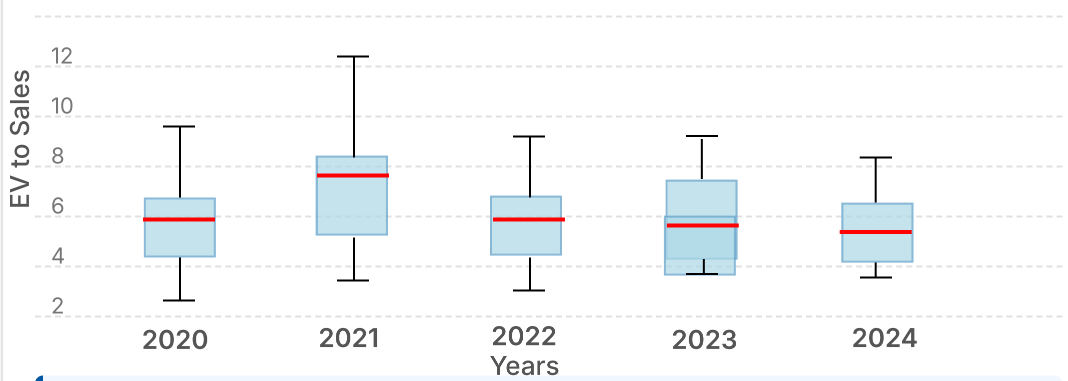
Developing ultra-compact, low-cost Raman analyzers on PICs using on-chip tunable lasers and hybrid silicon nitride + gallium arsenide platforms for real-time molecular monitoring.

Market Dynamics

Conventional photonics companies build on established product lines and proven reliability, though they face challenges around costs and scalability. PIC-based technologies introduce new opportunities through miniaturization and potential cost benefits, while still needing to address regulatory and validation requirements for broader adoption.

Valuations Metrics

EV to Sales Across Years - Public Companies



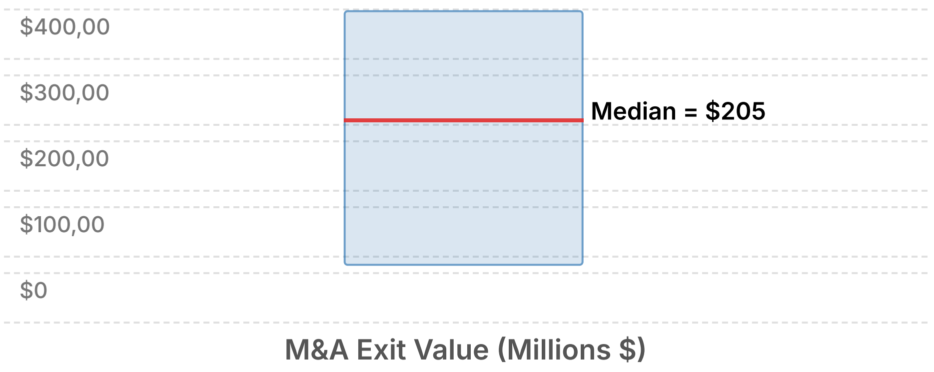
Key Finding

EV/Sales multiples are stable over the years, with most companies trading in the 4-6x range. The increase in 2021 was a result of the COVID-19 crisis.

Companies Used for Public Multiples Analysis

Mettler Toledo	Thermo Fisher Scientific	Repligen Corporation	Merck	Bruker Corporation	Dover Corporation
Sartorius AG	Danaher Corporation	Agilent Technologies	PerkinElmer, Inc.	Waters Corporation	Emerson Electric Co.

Exit value - Private Companies



Exit Value Analysis

Analysis of PAT market exits shows a range from $9M to $365M. This graph is based on 9 transactions.

Highlights

- No data was found on exits at the startup stage.
- Companies are usually acquired at the SME stage, when the technology has been de-risked and the company is generating over $5M in revenue.

M&A is driven by capabilities, portfolio and reach

Key Deal Highlights

High Multiple Acquisition

Repligen Corporation acquired C Technologies

Market-leading portfolio of spectroscopy products with inline real-time control capabilities.

$240M deal size | 10.13x Revenue multiple | 2019

Software Acquisition

Sartorius Stedim Biotech acquired Umetrics

Software tool for process monitoring and optimization, enhancing data analytics capabilities.

$72.5M deal size | 4.83x Revenue multiple | 2017

Recent Average Acquisition

Repligen acquired four analytical tools of 908 Devices

Complementary technology acquisition to strengthen analytical portfolio and capabilities.

$70M deal size | 5.88x Revenue multiple | 2025

Exit Analysis

$205M
Median PAT technology exit value

$72.5M
Median software exit value

~5x
Median revenue multiple

2 per year
Average exit frequency

Strategic M&A Drivers

1. Strengthen PAT capabilities
Add real-time measurement and control technologies to optimize existing tools and processes

2. Expand product portfolios
Broaden solution offerings to provide customers with end-to-end capabilities from a single provider

3. Enhance global reach
Extend geographic presence and enter new markets through strategic acquisitions

Conclusion

Market Conclusions

- PAT is **mission-critical** for modern bioprocessing, growing from $2B to $6B (13% CAGR) by 2033
- Optical technologies, especially **Raman spectroscopy**, dominate due to superior specificity and multiplexed capability
- Current adoption barriers: high cost ($50K-$250K), integration complexity, and stringent GMP compliance requirements
- M&A activity shows **consistent exits at SME stage** with 4-6x multiples, driven by capability expansion strategies
- By **leveraging the data** from innovative hardware into AI models that provide deep insights for bioprocess improvement, companies can unlock far more value than the hardware on its own

Role of PIC Technology

- **Cost reduction**: Can be 10 to 100 times cheaper than traditional systems
- **Miniaturization**: Multiple core components can be integrated on a chip. The technology of integrating multiple components of sensor systems on one chip allows for multiplexed sensing of multiple process variables simultaneously
- **Single-use capability**: Critical advantage for pharmaceutical applications requiring sterility
- **Scalability**: Multiple sensors become economically viable, enabling better process control
- **Trade-off**: PIC-based technologies offer disruptive potential with miniaturization and cost advantages, however traditional PAT companies still hold the advantage of established product lines

Strategic Implications

Market Strategy

- Focus on **dual market approach**: niche applications for early traction while developing pharma-ready solutions
- Prioritize partnerships with established PAT providers for **faster regulatory acceptance**

Technology Focus

- Ventures with **full-stack capabilities** (hardware + software + data analytics)
- Prioritize **GMP-compliant by design** approaches that address regulatory concerns early

Exit Potential

- Plan for **strategic acquisitions** with proven technology and initial revenue
- Target **4-6x multiples** with strategic buyers seeking capability expansion
- AI powered by proprietary hardware-derived data can command **premium valuations**

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