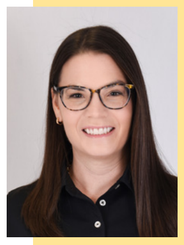
Top must-read Biopharma 4.0 articles*

Stay informed about the latest research embracing Biopharma 4.0 principles

1 Role of Artificial Intelligence in Revolutionizing Drug Discovery

Ashfaq Ur Rehman, Mingyu Li, Binjian Wu, Yasir Ali, Salman Rasheed, Sana Shaheen e, Xinyi Liu, Ray Luo, Jian Zhang., *Fundamental Research (accessed via Science Direct)*, 2024.



"This article offers a compelling overview of how AI is transforming drug discovery and biopharmaceutical manufacturing. I was particularly impressed by its clear articulation of how machine learning enhances process efficiency and product quality, while deepening our understanding of complex biological systems. It's a timely and insightful contribution to the evolving intersection of data science and drug development."

Maryann Cuellar
Life Science Industry Manager, Endress+Hauser

2 A Methodology for Identifying Current and Future Skills Gaps: Future-Proofing the Bioprocessing Sector As It Embraces Industry 4.0 Principles, Part 1

Beckwith, J.; Rooney, P.; Adams, G.; Goldrick, S.; Nixon, W.; Kourtzidis, S., *BioProcess International*, 2024.

Discusses identifying skill gaps in the bioprocessing sector as it adopts Industry 4.0 principles, emphasizing the need for new competencies in automation, data analytics, and cybersecurity.

3 A Methodology for Identifying Current and Future Skills Gaps: Future-Proofing the Bioprocessing Sector As It Embraces Industry 4.0 Principles, Part 2

Beckwith, J.; Rooney, P.; Adams, G.; Goldrick, S.; Nixon, W.; Kourtzidis, S., *BioProcess International*, 2024.

Outlines strategies to identify and address skills gaps in the bioprocessing sector, emphasizing the need for new competencies to leverage Industry 4.0 technologies effectively.

4 Biopharma 4.0 — the Talent Evolution

Beckwith, J.; Dool, R.; Rooney, P.; Thilagar, M.; Goldrick, S.; Nixon, W.; Kourtzidis, S., *BioProcess International,* 2023.

Studies the need for new skills in Biopharma 4.0, emphasizing data science, AI, and automation to meet the evolving demands of biomanufacturing.

5 AI-Enabled Digital Twins in Biopharmaceutical Manufacturing

Manzano, T.; Whitford, W., *BioProcess International*, 2023.

Highlights how AI-enabled digital twins enhance biopharmaceutical manufacturing by optimizing processes, improving real-time monitoring, and enabling predictive maintenance.

6 Biopharma Taps Bioprocessing 4.0, Benefits Start Flowing

Macdonald, G. J., *GEN - Genetic Engineering and Biotechnology News*, 2024.

"I thought this article did an excellent job of demonstrating how companies are adopting Biopharma 4.0 technologies. It thoroughly examines how data-driven decisions and inline analysis systems are enhancing speed, flexibility, and efficiency throughout the product lifecycle for many leading biomanufacturers."

Maryann Cuellar
Life Science Industry Manager, Endress+Hauser

7 The Role of Raman Spectroscopy in Biopharmaceuticals from Development to Manufacturing

Esmonde-White, K. A.; Cuellar, M.; Lewis, I. R., *Analytical Bioanalytical Chemistry*, 2021.

"I wrote my first review of Raman in bioprocessing in 2017, noticing that there had been a dearth of reviews on the topic since it was last mentioned in 2010. I was not expecting to write another review on this topic so quickly after the first review! But the field has been moving so quickly, with new reports of applications from early discovery to downstream bioprocessing to digital twins, that an updated review was certainly merited. I especially appreciate how this newer review shows the rapid acceptance of Raman in upstream bioprocessing, growing comfort with the technology, and emerging applications driven by the biopharmaceutical industry."

Karen Esmonde-White, PhD
Product Manager, Endress+Hauser

8 A roadmap to AI-driven in silico process development: bioprocessing 4.0 in practice

Moritz von Stosch, Rui MC Portela, Christos Varsakelis., *Current Opinion in Chemical Engineering (accessed via Science Direct)*, 2023.

Discusses hybrid modeling in biopharmaceutical processes, highlighting its advantages, implementation steps, and its role in enhancing efficiency and strategic development in the industry.

9 Transformation of Biopharmaceutical Manufacturing Through Single-Use Technologies: Current State, Remaining Challenges, and Future Development

Samaras, J. J.; Micheletti, M.; Ding, W., *Annual Review of Chemical and Biomolecular Engineering*, 2022.

Explores how single-use technologies are transforming biopharmaceutical manufacturing, enhancing process efficiency and flexibility, while addressing challenges in materials science and system standardization.

10 Raman Spectrometric PAT Models: Successful Transfer from Minibioreactors to Larger-Scale, Stirred-Tank Bioreactors

Classen, J.; Langer, M.; Jockwer, A.; Traenkle, J., *BioProcess International,* 2022.

Details the successful transfer of Raman spectrometric PAT models from minibioreactors to larger-scale stirred-tank bioreactors, enhancing bioprocess monitoring and control.

11 Systematic Assessment of Process Analytical Technologies for Biologics

Gillespie, C.; Wasalathanthri, D. P.; Ritz, D. B.; Zhou, G.; Davis, K. A.; Wucherpfennig, T.; Hazelwood, N., *Biotechnology and Bioengineering,* 2021

Highlights how PAT can optimize antibody purification by monitoring variable region interactions with Protein A, thus improving elution pH control and streamlining therapeutic antibody production.

12 The Race to Develop the Pfizer-BioNTech COVID-19 Vaccine: From the Pharmaceutical Scientists' Perspective

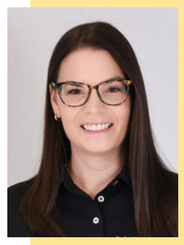
Lewis, L. M.; Badkar, A. V.; Cirelli, D.; Combs, R.; Lerch, T. F., *Journal of Pharmaceutical Sciences*, 2022.

"Impactful papers tell a story, in addition to reporting on data and results. For me, this paper underscores the incredible work of thousands to produce a safe and effective Covid-19 vaccine. It gave me a new appreciation for the many years spent to develop mRNA technology prior to 2020 and then the full cooperation of science, manufacturing engineering, and regulation to quickly bring a vaccine to the patients."

Karen Esmonde-White, PhD
Product Manager, Endress+Hauser

13 Biopharmaceutical Manufacturing: Historical Perspectives and Future Directions

Szkodny, A. C.; Lee, K. H., *Annual Review of Chemical and Biomolecular Engineering*, 2022.



"The authors provide a thoughtful and well-researched perspective on the evolution of biopharmaceutical manufacturing. I found the connection between historical milestones and current innovations particularly compelling, especially the shift toward platform processes and adaptive regulatory frameworks. It's a valuable resource for understanding how the industry has matured and where it's headed."

Maryann Cuellar
Life Science Industry Manager, Endress+Hauser

14 Hybrid modeling for biopharmaceutical processes: advantages, opportunities, and implementation

Harini Narayanan, Moritz von Stosch, Fabian Feidl, Michael Sokolov, Massimo Morbidelli, Alessandro Butté, *Frontiers in Chemical Engineering*, 2023.

Explores hybrid modeling in biopharmaceutical processes, detailing its benefits, implementation steps, and its potential to enhance efficiency and strategic development in the industry.

15 Ten Battlegrounds for Digital and Analytics in Life Sciences

Devereson, Alex; Llewellyn, Chris; Tinkoff, Dan; Vyaravanh, Manola , *McKinsey & Company* 2020.

Identifies ten key areas where digital and analytics can transform life sciences, emphasizing holistic approaches to innovation, clinical trials, and commercialization for substantial value creation.

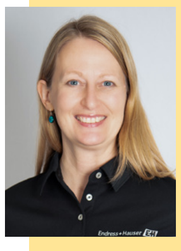
16 Digital Twins in Pharmaceutical and Biopharmaceutical Manufacturing: A Literature Review

Chen, Y.; Yang, O.; Sampat, C.; Bhalode, P.; Ramachandran, R.; Ierapetritou, M., *Processes,* 2020.

Highlights digital twins' potential in pharma and biopharma, noting gaps in PAT accuracy, real-time computation, and data security, and suggests solutions like NIRS, UV or Raman spectroscopy, and adaptive modeling.

17 Biopharmaceutical benchmarks 2022 | Nature Biotechnology

Walsh, G.; Walsh, E. , *Nature Biotechnology*, 2022.



"Professor Walsh has been publishing a survey on the status of biopharmaceuticals every 4 years since 2010. These surveys were very helpful for me to learn about the broad trends and important factors in advancing upstream biopharmaceuticals. I also refer to these articles routinely as a refresher and eagerly anticipate a new addition to this important series."

Karen Esmonde-White, PhD
Product Manager, Endress+Hauser

18

Rise of Single-Use Bioprocessing Technologies: Dominating Most R&D and Clinical Manufacture

Morrow Jr, K. J.; Langer, E. S., *American Pharmaceutical Review,* 2020.

Discusses how single-use bioprocessing technologies are increasingly being adopted in R&D and clinical manufacturing, offering flexibility and cost savings, though commercial adoption is slower due to regulatory and scalability challenges.

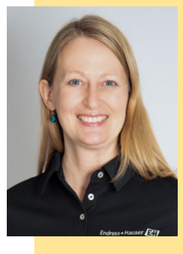
19 Utilizing Biopharma 4.0 to Boost Coronavirus 2019-nCoV Vaccine Efforts

Staff, GEN, *GEN - Genetic Engineering and Biotechnology News,* 2020.

Explores how Biopharma 4.0 technologies, including AI and automation, was accelerating COVID-19 vaccine development, enhancing manufacturing efficiency, and ensuring rapid response to future pandemics.

20 Understanding Pharmaceutical Quality by Design

Yu, L. X., Amidon, G.; Khan, M. A.; Hoag, S. W.; Polli, J.; Raju, G. K.; Woodcock, J., *PMC - National Library of Medicine*, 2022.



"Need an introduction to Quality by Design (QbD) and its many acronyms? This paper is a terrific reference that will guide you through the regulatory support of QbD and the processes to support the QbD framework. I especially appreciated the step-by-step guide on starting with the Quality Target Product Profile (QTPP), linking the critical material attributes (CMA) and critical quality attributes (CQA) to the QTPP, and defining the critical process parameters (CPP) to achieve the CMA or CQA. "

Karen Esmonde-White, PhD
Product Manager, Endress+Hauser

**The articles in this list are not presented in any particular ranked order.*

PI01611C/66/EN/01.25

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People for Process Automation