

Review

# Recent Advances in Optimization Methods for Machine Learning: A Systematic Review

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## Abstract

This systematic review explores modern optimization methods for machine learning, distinguishing between gradient-based techniques using derivative information and population-based approaches employing stochastic search. Key innovations focus on enhanced regularization, adaptive control mechanisms, and biologically inspired strategies to address challenges like scaling to large models, navigating complex non-convex landscapes, and adapting to dynamic constraints. These methods underpin core ML tasks including model training, hyperparameter tuning, and feature selection. While significant progress is evident, limitations in scalability and theoretical guarantees persist, directing future work toward more robust and adaptive frameworks to advance AI applications in areas like autonomous systems and scientific discovery.

**Keywords:** optimization methods; machine learning; gradient-based optimization; swarm intelligence; deep learning

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## 1. Introduction

Machine learning has witnessed transformative progress driven by deep neural networks [1] and generative architectures such as transformers [2] and diffusion models [3]. These innovations enable unprecedented performance in tasks that span perception, language understanding, and content synthesis, marking a shift toward scalable and adaptive systems.

However, the practical realization of these advances hinges on solving complex optimization problems. Training objectives typically combine empirical risk minimization (e.g., cross-entropy loss for classification) and regularization (e.g.,  $L_1/L_2$  penalties) to balance accuracy and generalization [4,5]. Although unconstrained optimization suffices for tasks such as linear regression [6], modern applications demand constrained formulations, from fairness-aware learning [7] to non-negative matrix factorization [8]. Recent studies highlight the challenges of scaling optimization to trillion-parameter models, where adaptive momentum clipping, memory-efficient strategies, and second-order methods such as natural gradient [9] and the memory-efficient framework proposed by Liu et al. [10] become critical to prevent divergence. A critical challenge lies in the duality between regularization and explicit constraints:  $L_1$  regularization, for example, induces sparsity equivalent to a constraint on the  $L_1$  norm [6]. Furthermore, non-convex landscapes in deep networks,

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**Karin Nielsen-Saines**



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